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THERMOPHYSICAL AND ELECTRICAL PROPERTIES OF METAL MATRIX COMPOSITES

P. D. DESAI, T. K. CHU, T. C. CHI, R. A. MATULA, AND H. H. LI
Thermophysical and Electronic Properties Information Analysis Center

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This report presents the available experimental data and information compiled from the scientific and technical literature on five properties of eight groups of metal matrix composites. The five properties are the thermal linear expansion, thermal conductivity, specific heat, thermal emittance, and electrical resistivity. The eight groups of metal matrix composites are the various composites of aluminum and aluminum alloy matrices, copper matrix, lead matrix, magnesium matrix, nickel and nickel alloy matrices, titanium and titanium alloy matrices, tungsten matrix, and zinc matrix. Most of the data are for aluminum

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PREFACE

This technical report was prepared by the Thermophysical and Electronic Properties Information Analysis Center (TEPIAC), a Department of Defense Information Analysis Center. This Center is operated by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana, under Contract No. DLA900-79-C-1007 with the Defense Logistics Agency (DLA), Alexandria, Virginia, with Mr. J. L. Blue(Hq. DLA) being the IAC Program Manager, and under the technical direction of the Army Materials and Mechanics Research Center (AMMRC), Watertown, Massachusetts, with Mr. Samuel Valencia being the Contracting Officer's Technical Representative.

This is a state-of-the-art report on the thermophysical and electrical properties of metal matrix composites, aiming at presenting all the available data and information on all the properties covered by TEPIAC. However, data and information have been found only for five properties and eight groups of metal matrix composites. The available data and information are presented in this report in a comprehensive and detailed form making it possible for all interested users of the data to have access to the original data without having to duplicate the laborious and costly process of comprehensive search of the literature and meticulous extraction of the data and information.

The data contained in this report have been obtained from a total of 41 technical reports and papers, 22% of them coming from foreign sources. It is suspected that a significant number of more recent reports generated under DOD sponsorship have not been reported to the DDC and therefore are not readily available. A special effort will be made in the future to uncover such reports if they exist.

It is hoped that this work will prove useful to engineers and scientists working on various engineering research and development programs. As metal matrix composites are candidates for structural materials for aircrafts and spacecrafts, this report should constitute a valuable source of data and information for aerospace industry as well as defense applications.

It is our plan to update and upgrade this report periodically through the critical evaluation of the raw data reported herein and from any additional sources that may come to our attention.

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Director of CINDAS
Distinguished Atkins Professor
of Engineering
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West Lafayette, Indiana
December 1979

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INTRODUCTION

The purpose of this report is to present the available experimental data and information on the thermophysical and electrical properties of metal matrix composites. These data have been found as a result of an exhaustive search of the DDC, NTIS, and TEPIAC's own data banks. The resulting data are from research documents published over the period 1957 to 1979. Although the literature search was aimed at seeking data for all the thermophysical and electronic properties of metal matrix composites, there are only five properties for which data have been found. These are the thermal linear expansion, thermal conductivity, specific heat, thermal emittance, and electrical resistivity. Furthermore, most of the data are for the thermal linear expansion. There are eight groups of metal matrix composites for which data have been found: these are the various composites of aluminum and aluminum alloy matrices, copper matrix, lead matrix, magnesium matrix, nickel and nickel alloy matrices, titanium and titanium alloy matrices, tungsten matrix, and zinc matrix. Most of the data are for aluminum and aluminum alloy matrix composites. No attempt has been made to evaluate the compiled data at this time.

The organization of this report is as follows. Each chapter is for the thermophysical and electrical properties of a distinct group of metal matrix composites and the chapters are arranged in the alphabetical order of the various metal matrices. Within a chapter each section is for a particular kind of fiber, filament,

wire, or whisker. Within a given section the data for each property are presented in both tabular and graphical forms and the order of the properties is arranged such that the property with the more abundant data comes first. Before presenting the numerical data, a short discussion of the data together with references is given, which is followed by a data table and one or more figures. Thus each section constitutes a self-contained unit. In the data table each data set is accompanied by a statement pertaining to the sample identification, specification, and remarks. In the figure all data for a given property are shown except where the data points are too close together; in such case some of the data points may be omitted from the figure for the sake of clarity and these omitted data points are indicated in the data table by asterisks. In addition, when there is only a single data point available for a property of a metal matrix composite, no figure is given for that property.

The technical terms, symbols, and units used in this report are defined below:

c_p	Specific heat, in J kg^{-1}K^{-1}
$\Delta L/L_0$	Thermal linear xpansion, in %
ΔL	change in length of a material compared to a reference length
L_0	reference length of a material at 293 K

T	Temperature, in K
ϵ	Thermal emittance, dimensionless
λ	Thermal conductivity, in W $m^{-1}K^{-1}$
ρ	Electrical resistivity, in $10^{-8}\Omega$ m

Data on the thermal linear expansion are given as percent elongation, $\Delta L/L_0$(%). In order to compare all the available data from the literature on the same basis, the thermal expansion has been arbitrarily set to zero at 293 K, which is the reference temperature. In cases where the reference temperatures used by the authors are different from 293 K, the data are corrected such that the $\Delta L/L_0$(%) value at 293 K is zero. This correction factor used is called zero point correction and is given in the "Specifications and Remarks" column of the data table.

An Index to Materials and Properties at the end of this report will assist in the rapid location of information on materials and properties for which data are reported.

THERMOPHYSICAL AND ELECTRICAL PROPERTIES OF METAL MATRIX COMPOSITES

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CHAPTER 1

ALUMINUM AND ALUMINUM ALLOY MATRIX COMPOSITES

1.1. BORON FIBER, ALUMINUM MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

There are 14 data sets available for the thermal expansion of boron fiber aluminum matrix composites [1,2]. Wolff and Hill [1] reported the data for composites with 10, 30, and 60 volume percent continuous aligned and discontinuous random boron fibers. Salibekov et al. [2] reported data for both heating and cooling cycles for composites with 10 and 30 volume percent boron fibers in the directions parallel and perpendicular to the fiber axis. Salibekov et al. [2] observed a permanent contraction of about 0.1% after a heating and cooling cycle and the thermal expansion perpendicular to the fiber axis being about four times higher than that along the fiber axis at 730 K.

THERMAL CONDUCTIVITY

There are two references [1,3] in which the thermal conductivity of boron fiber aluminum matrix composite are reported. Ref. [1] reported values for a composite of low fiber content as a function of temperature (~ 326 - 366 K). Ref. [3] reported the change of thermal conductivity value with fiber volume content, and with heat flow direction (parallel and perpendicular to the fiber direction).

ELECTRICAL RESISTIVITY

Only two sets of measurements on the electrical resistivity of an aluminum-boron composite, containing 60 volume percent uniaxial boron fibers, have been reported from 78 to 400 K with the electrical current parallel and perpendicular to the fibers from [4]. Both transverse and longitudinal resistivities approach a linear behavior at higher temperatures. However, at low temperature there is a noticeable difference with the longitudinal resistivity exhibiting a normal metallic behavior.

REFERENCES

1. Wolff, E.G. and Hill, R.J., U.S. Air Force Rept. AFML-TR-67-140, 163 pp., 1967. [AD-816 439]
2. Salibekov, S.E., Portnoi, K.I., and Chubarov, V.M., High Temp., 10(4), 702-6, 1972.
3. Chamis, C., NASA Rept. TN D-6696, 27 pp., 1972. [N72-18582]
4. Abukay, D., Rao, K.V., Arajs, S., and Yao, Y.D., Fibre Sci. Technol., 10(4), 313-8, 1977.

TABLE 1. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF BORON FIBER, ALUMINUM MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %; Thermal Conductivity, λ, W m^{-1} K^{-1}; Electrical Resistivity, ρ, 10^{-8} Ω m]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	293 366 405 589	0.000 0.066 0.135 0.350	Aluminum with continuous aligned boron fibers, 10 volume % boron fibers, density 151 lb ft^{-3}; quartz tube dilatomer; measurements direction not reported; values calculated from the reported tabular values of mean coefficient.	Wolff, E. G., and Hill, R. J., 1967
2 [1]	293 377 477 589	0.000 0.058 0.111 0.184	Similar to the above.	Wolff, E. G., and Hill, R. J., 1967
3 [1]	293 377 422 589	0.000 0.122 0.166 0.295	Similar to the agove except discontinuous 10 volume % boron fibers and density 164 lb ft^{-3}.	Wolff, E. G., and Hill, R. J., 1967
4 [1]	293 383 505 589	0.000 0.196 0.489 0.702	Similar to the above except discontinuous random fibers and density 165 lb ft^{-3}.	Wolff, E. G., and Hill, R. J., 1967
5 [1]	293 355 450 589	0.000 0.108 0.362 0.730	Similar to the above except density 166 lb ft^{-3}.	Wolff, E. G., and Hill, R. J., 1967

TABLE 1. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF BORON FIBER, ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
6 [1]	293	0.000	Similar to the above except continuous 30 volume % boron fibers and density 154 lb ft^{-3}.	Wolff, E. G., and Hill, R. J., 1967
	366	0.059		
	466	0.113		
	589	0.195		
7 [1]	293	0.000	Similar to the above.	Wolff, E. G., and Hill, R. J., 1967
	377	0.084		
	489	0.162		
	589	0.215		
8 [1]	293	0.000	Similar to the above except discontinuous random boron fibers and density 153 lb ft^{-3}.	Wolff, E. G., and Hill, R. J., 1967
	377	0.134		
	544	0.431		
	594	0.478		
9 [1]	293	0.000	Similar to the above except continuous aligned 60 volume % boron fibers and density 157 lb ft^{-3}.	Wolff, E. G., and Hill, R. J., 1967
	339	0.051		
	405	0.101		
	589	0.209		
10 [2]	293	0.000	Boron fibers 10 volume % aluminum matrix composites of 100μ is prepared by a thermal diffusion compound of a bundle of aluminum foil and boron fibers in alternate layers; test specimen 30 x 4 x 3 mm plates; heated in argon atmosphere at 3 deg. $min.^{-1}$ accuracy of measurements ±5%; dilatometry;	Salibekov, S. E., Portnoi, K. I., and Chubarov, V. M., 1972
	352	0.105		
	414	0.179		
	475	0.217		
	528	0.238		
	575	0.247		
	642	0.255		
	676	0.255		
	719	0.257		

TABLE 1. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF BORON FIBER, ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
10 (cont.) [2]	772	0.261	heating cycle measurements along fiber axis; data extracted from the graph. Zero point correction is -0.002%.	
11 [2]	307	0.007	Similar to the above except cooling cycle; zero point correction is 0.062%.	Salibekov, S. E., et al., 1972
	383	0.043		
	440	0.072 *		
	491	0.100		
	549	0.138		
	606	0.172		
	661	0.210		
	704	0.252		
	731	0.281		
	752	0.303		
	772	0.325		
12 [2]	293	0.000	Similar to the above except 30 volume % fibers; heating cycle; zero point correction is -0.002%.	Salibekov, S. E., et al., 1972
	356	0.070		
	417	0.109		
	475	0.129		
	536	0.147		
	608	0.167		
	655	0.187		
	706	0.211		
	754	0.239		
	774	0.245		

TABLE 1. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF BORON FIBER, ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
13 [2]	290	-0.002	Similar to the above except cooling cycle; zero point correction is 0.012%.	Salibekov, S. E., et al., 1972
	352	0.034 *		
	441	0.076		
	508	0.112		
	574	0.140		
	640	0.172		
	699	0.206		
	737	0.231		
	761	0.247 *		
	774	0.259		
14 [2]	299	0.012 *	Similar to the above except heat cycle and measurements perpendicular to the fiber axis, zero point correction is 0.020%.	Salibekov, S. E., et al., 1972
	303	0.020		
	351	0.148		
	369	0.201		
	421	0.337		
	422	0.352		
	470	0.480		
	520	0.639		
	572	0.790		
	614	0.941		
	671	1.129		
	697	1.226		
	730	1.348		
	T	λ	THERMAL CONDUCTIVITY	
1 [1]	327	58.	Prepared by hot-pressing continuous boron fiber mats and aluminum foil; plates about 5 in. x 5 in. were hot pressed at 932°F and 4000 psi; fiber	Wolff, E. G. and Hill, R. J., 1967
	327	50.		
	349	37.		
	366	35.		

TABLE 1. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF BORON FIBER, ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
			THERMAL CONDUCTIVITY (cont.)	
	T	λ		
1 (cont.) [1]			volume content 15%; density 2.67 gcm^{-3}; specimen machined to a diameter of 1 inch and >1/4 inch thick; measured by a steady state cut-bar method with heat flow perpendicular to fibers; data points extracted from graph.	
2 [1]	332 332	351. 332.	Prepared by vacuum casting; discontinuous random fibers; fiber volume content 30%; density 2.64 gcm^{-3}; specimen 1 inch in diameter and >1/4 inch thick; measured by a steady-state cut-bar method; data points extracted from graph.	Wolff, E. G. and Hill, R. J., 1967
			ELECTRICAL RESISTIVITY	
	T	ρ		
1 [4]	79 100 120 140 180 210 240 280 303 331 370 400	1.07 1.52 2.15 2.77 3.95 5.03 5.83 7.00 7.73 8.62 9.80 10.6	60 volume % uniaxial continuous boron fibers contains in the specimen, which was obtained from Commonwealth Scientific Corporation; the aluminum matrix of this composite of commercial grade type 6061 was made using ribbons of thickness 2.4×10^{-3} cm and width 3.9×10^{-2} cm helically wound around boron fibers; the diameter of the bare boron fibers is approximately 0.02 cm; the specimen dimensions 2 x 2 x 50 mm, boron fiber parallel to long axis; the standard tow probe method is used for measuring the electrical resistivity.	Abukay, D., Rao, K. V., Arajs, S., and Yao, Y. D., 1977

TABLE 1. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF BORON FIBER, ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	ρ	ELECTRICAL RESISTIVITY (cont.)	
2 [4]	79	13.4	60 volume % uniaxial continuous boron fibers contains in the specimen; the specimen dimensions 2 x 2 x 15 mm, boron fiber perpendicular to long axis; the standard tow probe method is used for measuring the electrical resistivity.	Abukay, D., et al., 1977
	100	15.3		
	120	17.3		
	140	19.3		
	180	23.4		
	210	26.3		
	240	29.5		
	280	33.5		
	302	35.5		
	360	40.9		
	380	42.7		

*Not shown in figure.

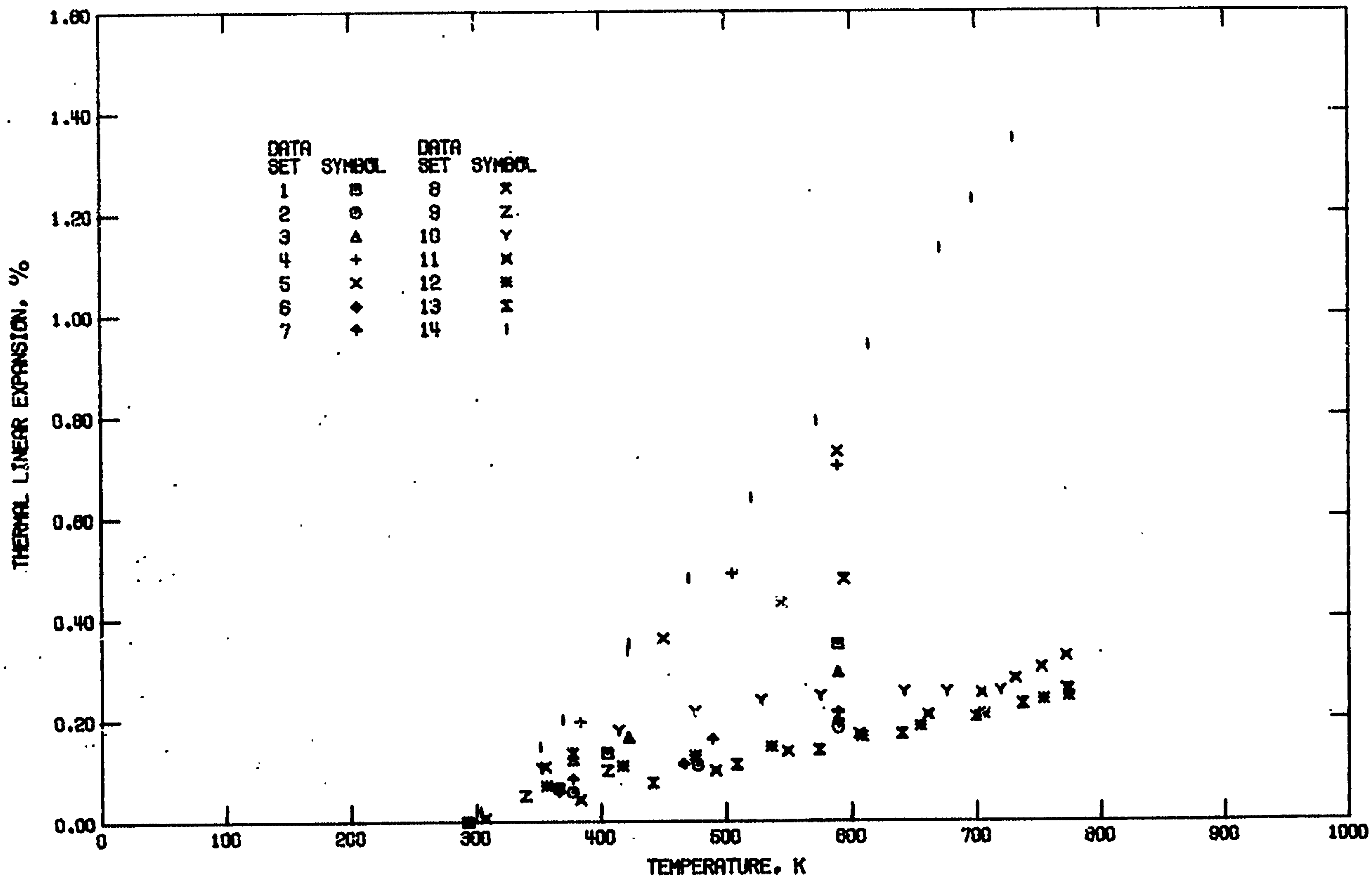

FIGURE 1. THERMAL LINEAR EXPANSION OF BORON FIBER, ALUMINUM MATRIX COMPOSITE.

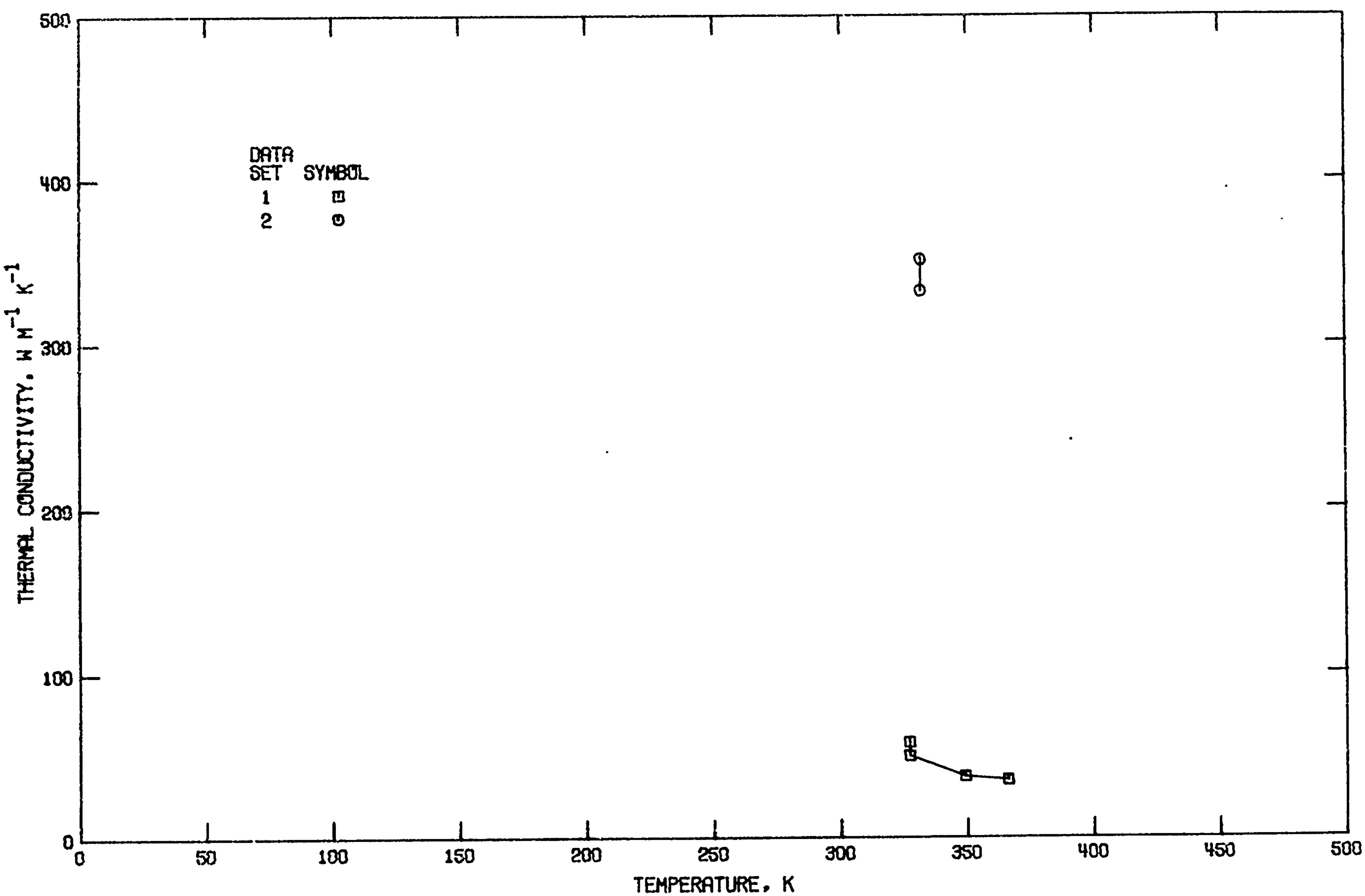

FIGURE 2. THERMAL CONDUCTIVITY OF BORON FIBER, ALUMINUM MATRIX COMPOSITE.

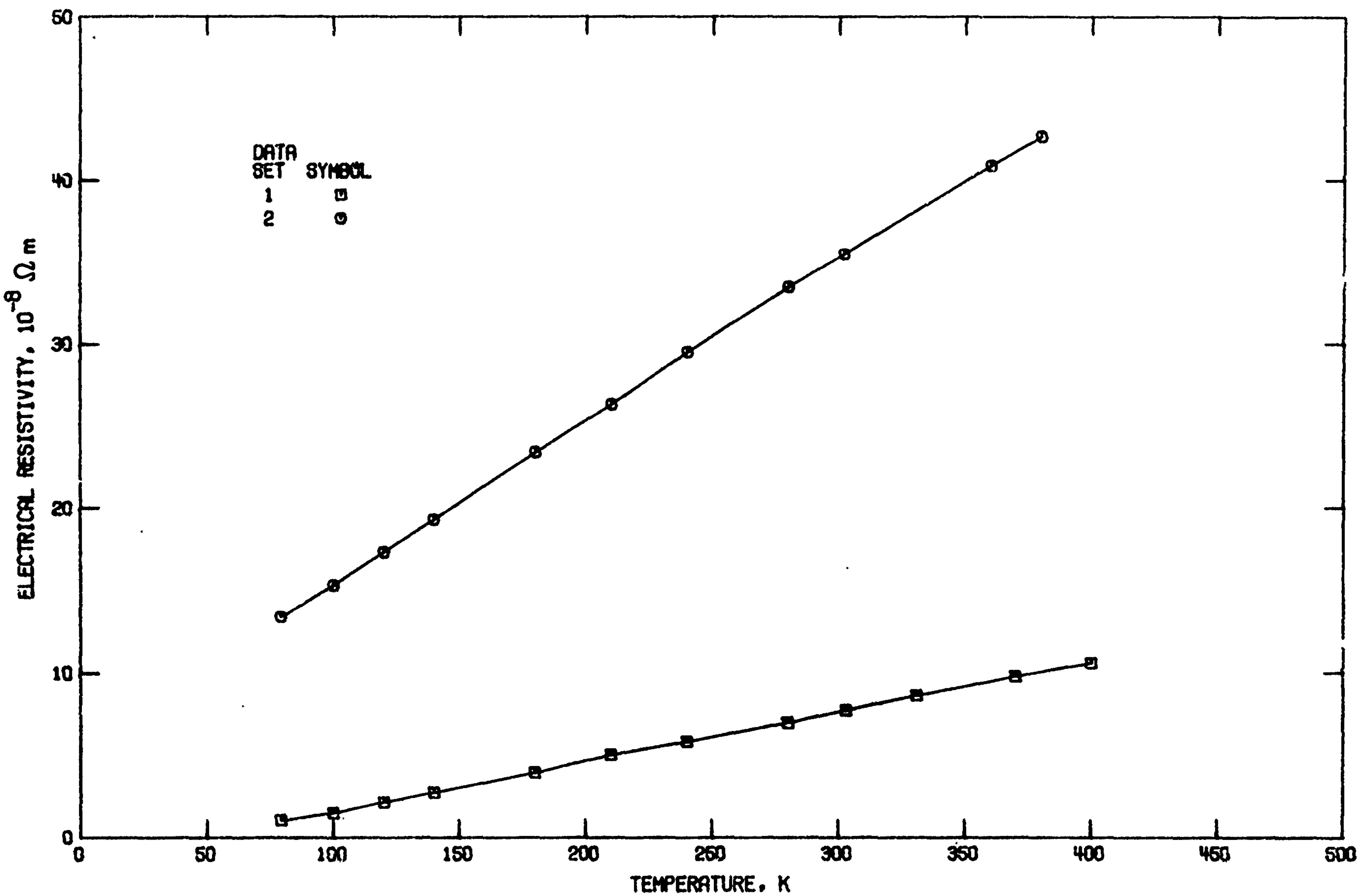

FIGURE 3. ELECTRICAL RESISTIVITY OF BORON FIBER, ALUMINUM MATRIX COMPOSITE.

TABLE 2. DATA ON THE THERMAL CONDUCTIVITY OF BORON FIBER, ALUMINUM MATRIX COMPOSITE(FIBER VOLUME DEPENDENCE)

[Fiber Volume, V, % ;Thermal Conductivity, λ, W m^{-1} K^{-1}]

Data Set [Ref.]	Vol.	Prop.	Specifications and Remarks	Author(s), Year
	V	λ	THERMAL CONDUCTIVITY	
1 [3]	40.	72.4	Pseudoisotropic boron fiber aluminum matrix laminate; heat flow in the plane of laminate; ; room temperature assumed; smoothed data from graph.	Chamis, C., 1972
	50.	60.2		
	60.	47.7		
	70.	35.5		
	75.	29.4		
2 [3]	40.	55.2	Similar to the above except heat flow perpendicular to laminate.	Chamis, C., 1972
	50.	44.7		
	60.	35.4		
	70.	26.6		
	75.	22.9		

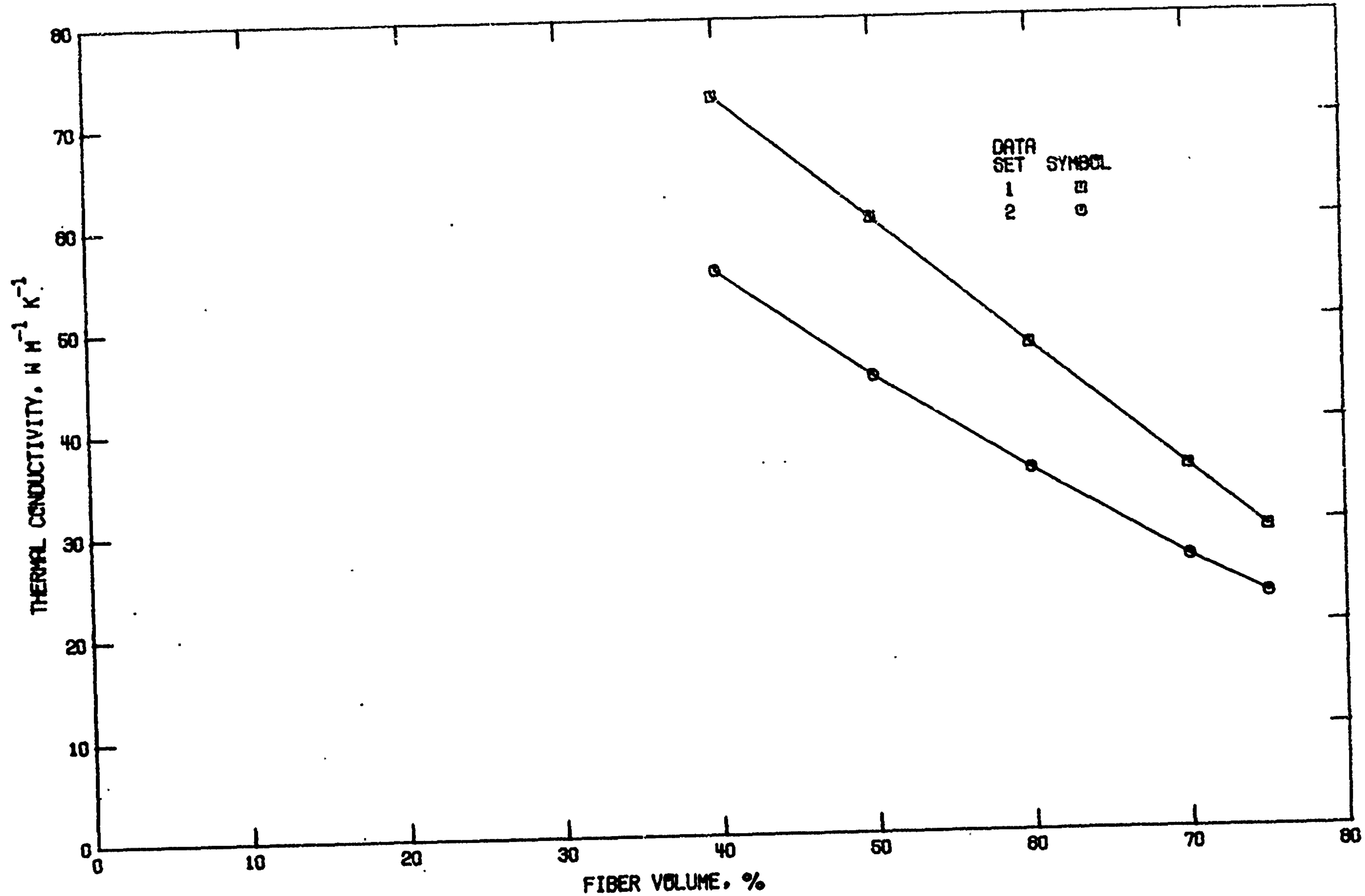

FIGURE 4. THERMAL CONDUCTIVITY OF BORON FIBER, ALUMINUM MATRIX COMPOSITE.

1.2. GRAPHITE FIBER, ALUMINUM MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Salibekov et al. [1] reported thermal expansion data for composites containing 45 volume percent graphite fibers. Thermal expansion of this composites increased upon heating to 150°C, decreased upon further heating to 500°C, and the specimen contracted to a constant value of about 0.08% after cooling to room temperature. The specimen upon a second cooling cycle showed a similar but less pronounced trend. This unusual nature of the thermal expansion was explained as due to the relaxation of residual stresses in the material which were generated on cooling the material from the sintering temperature (1000°C). These stresses compress the fibers and extend the matrix.

REFERENCE

1. Salibekov, S.E., Portnoi, K.I., and Chubarov, N.M., High Temp., 10(4), 702-6, 1972.

TABLE 3. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, ALUMINUM MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	293	0.000	45 volume % graphite fiber aluminum matrix composites are obtained by steeping the fibers in liquid aluminum under pressure; test specimen 30 x 4 x 3 mm plates, heated in argon atmosphere at 3 deg. min.$^{-1}$, dilatometry, accuracy ±5%; first heating measurements; direction of measurements not reported; data extracted from figure.	Salibekov, S. E., Portnoi, K. I., and Chubarov, V. M., 1972
	318	0.064		
	347	0.130		
	369	0.162		
	400	0.191		
	432	0.207		
	459	0.205		
	473	0.198		
	510	0.178		
	556	0.130		
	584	0.105		
	622	0.074		
	673	0.033		
	700	0.010		
	730	-0.008 *		
	752	-0.019		
	770	-0.019		
2 [1]	293	0.000	Similar to the above except first cooling measurements; zero point correction 0.023%.	Salibekov, S. E., et al., 1972
	370	-0.002		
	436	-0.002 *		
	472	-0.002		
	535	-0.004 *		
	575	-0.006		
	621	-0.008 *		
	650	-0.008		
	671	-0.008 *		

TABLE 3. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	<u>THERMAL LINEAR EXPANSION</u> (cont.)	
2 (cont.)	713	-0.010		
[1]	736	-0.010 *		
	768	-0.003		
3	293	0.000	Similar to the above except second heating cycle.	Salibekov, S. E., et al., 1972
[1]	319	0.061 *		
	347	0.107		
	369	0.139		
	397	0.159		
	423	0.164		
	454	0.162		
	472	0.153		
	517	0.121		
	546	0.094		
	574	0.074		
	605	0.051		
	633	0.037		
	671	0.019		
	704	0.006		
	735	-0.001		
	768	-0.008		
4	295	0.000 *	Similar to the above except second cooling cycle; zero point correction is 0.012%.	Salibekov, S. E., et al., 1972
[1]	370	-0.002		
	426	-0.001		
	472	-0.001 *		
	538	-0.003		
	572	-0.005 *		
	623	-0.007		

TABLE 3. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
4 (cont.) [1]	671	-0.007		
	734	-0.009		
	755	-0.009		
	768	-0.002		

*Not shown in figure.

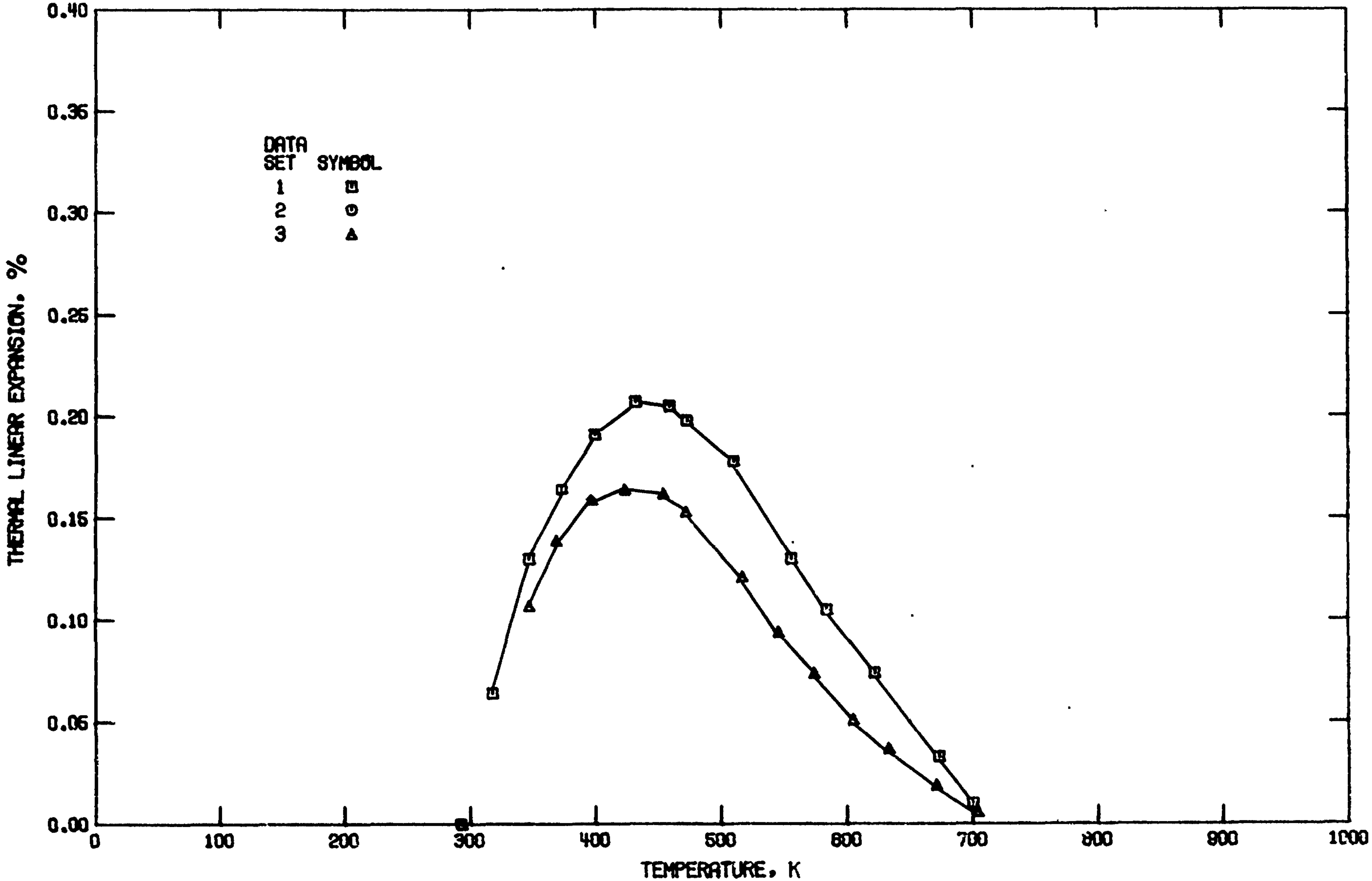

FIGURE 5. THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, ALUMINUM MATRIX COMPOSITE .

1.3. Kh18N10T FIBER, AD1 ALUMINUM MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Karpinos et al. [1] reported thermal expansion data for AD1 aluminum (>99.3%Al, 0.35% Si, 0.05% Cu, and 0.03% Fe) reinforced with 12 and 20 volume percent Kh18N10T (Russian equivalent of AISI 321 stainless steel) fibers. Introduction of fibers into the matrix and increasing its concentration caused the coefficient of thermal expansion to decrease monotonically. Karpinos et al. [1] stated that the angle between the fiber direction in a specimen and the specimen's longitudinal axis strongly affects the coefficient of thermal expansion.

THERMAL CONDUCTIVITY

The thermal conductivity of Kh18N10T fiber aluminum matrix composite has been investigated by Karpinos et al. [2]. The fiber content of the specimens varies from 7.5 to 53 volume percent. The thermal conductivity values over a wide temperature range (~330 - 900 K) for heat flow at 0°, 30°, 60°, and 90° with respect to the fiber direction are reported. For the sake of clarity, only values for the parallel (0°) and the perpendicular (90°) directions were illustrated in the figure. In general, values for intermediate heat flow directions fall between the values for heat flow at 0 deg. and 90 deg..

REFERENCES

1. Karpinos, D.M., Kadyrov, V.Kh., Klimenko, V.S., Fefer, V.Ya., and Miroshnikova, T.K., Sov. Powder Met. Metal.

Ceram., (4), 301-3, 1974.

2. Karpinos, D.M., Klimenko, V.S., and Kadyrov, V.H., High Temp. High Pressures, 5(1), 13-7, 1973.

TABLE 4. DATA ON THE THERMOPHYSICAL PROPERTIES OF Kh18N10T FIBER, AD1 ALUMINUM MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %; Thermal Conductivity, λ, W m^{-1} K^{-1}]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	189	-0.218	AD1 aluminum base composite reinforced with steel fibers; composites prepared by technique of elevated temperature densification of packs composed of alternating matrix foil and reinforcing fiber layers, 12 vol. % Kh18N10T steel; thermal expansion of composite was measured on 4-mm square by 60 mm long prismatic specimens cut from densified blanks oriented parallel to the direction of fiber orientation; volume fraction of fibers determined on micrographs of specimen cross sections; thermal expansion measured on chevenard type dilatometer in argon atmosphere; heating rate 2° C min^{-1}; values obtained by integrating graphically reported instantaneous coefficient data.	Karpinos, D. M., Kadyrov, V. Kh., Klimenko, V. S., Fefer, V. Ya., and Miroshnikova, T. K., 1974
	224	-0.145		
	264	-0.062		
	307	0.031		
	366	0.161		
	433	0.313		
	484	0.430		
	583	0.658		
	634	0.781		
	677	0.887		
	709	0.965		
	756	1.083		
	792	1.174		
2 [1]	189	-0.160	Similar to the above except 20 volume % Kh18N10T steel fibers.	Karpinos, D. M., et al., 1974
	244	-0.077		
	299	0.010		
	342	0.081		
	382	0.147		
	425	0.223		

TABLE 4. DATA ON THE THERMOPHYSICAL PROPERTIES OF Kh18N10T FIBER, AD1 ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
2 (cont.) [1]	480	0.321		
	524	0.401		
	583	0.512		
	630	0.604		
	701	0.747		
	756	0.862		
	792	0.937		
3 [1]	300	0.014 *	Similar to the above except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 90 degrees; values calculated from graphically reported values of mean coefficient.	Karpinos, D. M., et al., 1974
	400	0.220 *		
4 [1]	300	0.015 *	Similar to the above except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 60 degrees.	Karpinos, D. M., et al., 1974
	400	0.227 *		
5 [1]	300	0.014 *	Similar to the above except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 45 degrees.	Karpinos, D. M., et al., 1974
	400	0.211 *		
6 [1]	300	0.014 *	Similar to the above except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 30 degrees.	Karpinos, D. M., et al., 1974
	400	0.207 *		

TABLE 4. DATA ON THE THERMOPHYSICAL PROPERTIES OF Kh18N10T FIBER, AD1 ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
7 [1]	300	0.013 *	Similar to the above except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 10 degrees.	Karpinos, D. M., et al., 1974
	400	0.197 *		
8 [1]	189	-0.115	Similar to the above except 30 volume % Kh10N10T steel fibers.	Karpinos, D. M., et al., 1974
	236	-0.066		
	287	-0.007		
	342	0.063		
	520	0.324		
	567	0.402		
	599	0.455		
	646	0.536		
	693	0.618		
	733	0.688		
	780	0.775		
	T	λ	THERMAL CONDUCTIVITY	
1 [2]	336	201.	18-10 tye chromium nickel steel (1Kh18N10T), continuous fiber in technically pure AD-1 aluminum, obtained by consolidation at high temperatures; fiber content 7.5% by volume; prismatic specimen 4 x 4 x 100 mm³, cut from plate; specimen axis at 0° from the fiber direction; measured by a steady state method; data points taken from graph.	Karpinos, D. M., Klimenko, V. S., and Kadyrov, V. H., 1973
	338	204.		
	392	203.		
	401	202.		
	506	204.		
	514	206.		
	523	205.		
	618	211.		
	628	212.		
	765	218.		
	775	217.		
	868	220.		
	880	220.		
	891	220.		

TABLE 4. DATA ON THE THERMOPHYSICAL PROPERTIES OF Kh18N10T FIBER, AD1 ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
2 [2]	345	200.	Similar to the above except specimen axis at 30° to fiber direction.	Karpinos, D. M., et al., 1973
	357	199.		
	415	202.		
	427	202.		
	576	206.		
	591	206.		
	802	218.		
	810	217.		
	818	219.		
3 [2]	363	196.	Similar to the above except specimen axis at 60° to fiber direction.	Karpinos, D. M., et al., 1973
	376	196.		
	467	201.		
	475	201.		
	684	209.		
	692	210.		
	703	212.		
	715	208.		
	845	215.		
	854	216.		
	832	215.		
4 [2]	351	190.	Similar to the above except specimen axis at 90° to fiber direction.	Karpinos, D. M., et al., 1973
	413	193.		
	421	191.		
	535	197.		
	783	210.		
	823	211.		
	835	210.		
	845	212.		

TABLE 4. DATA ON THE THERMOPHYSICAL PROPERTIES OF Kh18N10T FIBER, AD1 ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
5 [2]	341	153.	Similar to the above except fiber content 31% by volume; specimen axis at 0° to fiber direction.	Karpinos, D. M., et al., 1973
	395	153.		
	403	154.		
	411	152.		
	587	157.		
	596	157.		
	718	165.		
	833	172.		
	842	174.		
	852	172.		
	864	173.		
6 [2]	327	148.	Similar to the above except specimen axis at 30° to fiber direction.	Karpinos, D. M., et al., 1973
	337	148.		
	442	154.		
	451	155.		
	622	161.		
	625	157.		
	631	160.		
	794	167.		
	800	168.		
	877	170.		
	885	172.		
7 [2]	352	139.	Similar to the above except specimen axis at 60° to fiber direction.	Karpinos, D. M., et al., 1973
	364	138.		
	515	140.		
	527	142.		
	540	141.		

TABLE 4. DATA ON THE THERMOPHYSICAL PROPERTIES OF Kh18N10T FIBER, AD1 ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
7 (cont.)	724	149.		
[2]	734	149.		
	745	151.		
	757	152.		
	852	156.		
	858	156.		
	862	157.		
8	335	129.	Similar to the above except specimen axis at 90° to fiber direction.	Karpinos, D. M., et al., 1973
[2]	341	126.		
	366	125.		
	453	128.		
	463	128.		
	588	133.		
	596	133.		
	608	135.		
	681	134.		
	693	134.		
	697	132.		
	830	138.		
	842	138.		
9	368	107.	Similar to the above except fiber content 53% by volume, specimen axis at 0° to fiber direction.	Karpinos, D. M., et al., 1973
[2]	373	107.		
	486	107.		
	491	109.		
	499	107.		
	567	109.		
	720	114.		

TABLE 4. DATA ON THE THERMOPHYSICAL PROPERTIES OF Kh18N10T FIBER, AD1 ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	<u>THERMAL CONDUCTIVITY</u> (cont.)	
9 (cont.)	735	113.		
[2]	741	114.		
	759	114.		
	764	113.		
10	338	97.	Similar to the above except specimen	Karpinos, D. M.,
[2]	348	98.	axis at 30° to fiber direction.	et al., 1973
	431	97.		
	439	99.		
	451	99.		
	625	103.		
	635	102.		
	644	104.		
	826	112.		
	842	112.		
	848	114.		
11	387	85.	Similar to the above except specimen	Karpinos, D. M.,
[2]	400	87.	axis at 60° to fiber direction.	et al., 1973
	408	85.		
	456	86.		
	468	86.		
	580	87.		
	584	85.		
	799	93.		
	809	94.		
	822	94.		
	830	94.		

TABLE 4. DATA ON THE THERMOPHYSICAL PROPERTIES OF Kh18N10T FIBER, AD1 ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
12 [2]	369	77.	Similar to the above except specimen axis at 90° to fiber direction.	Karpinos, D. M., et al., 1973
	377	75.		
	381	75.		
	510	81.		
	514	79.		
	663	83.		
	669	85.		
	675	84.		
	780	90.		
	791	88.		
	811	91.		
	849	93.		
	859	92.		

*Not shown in figure.

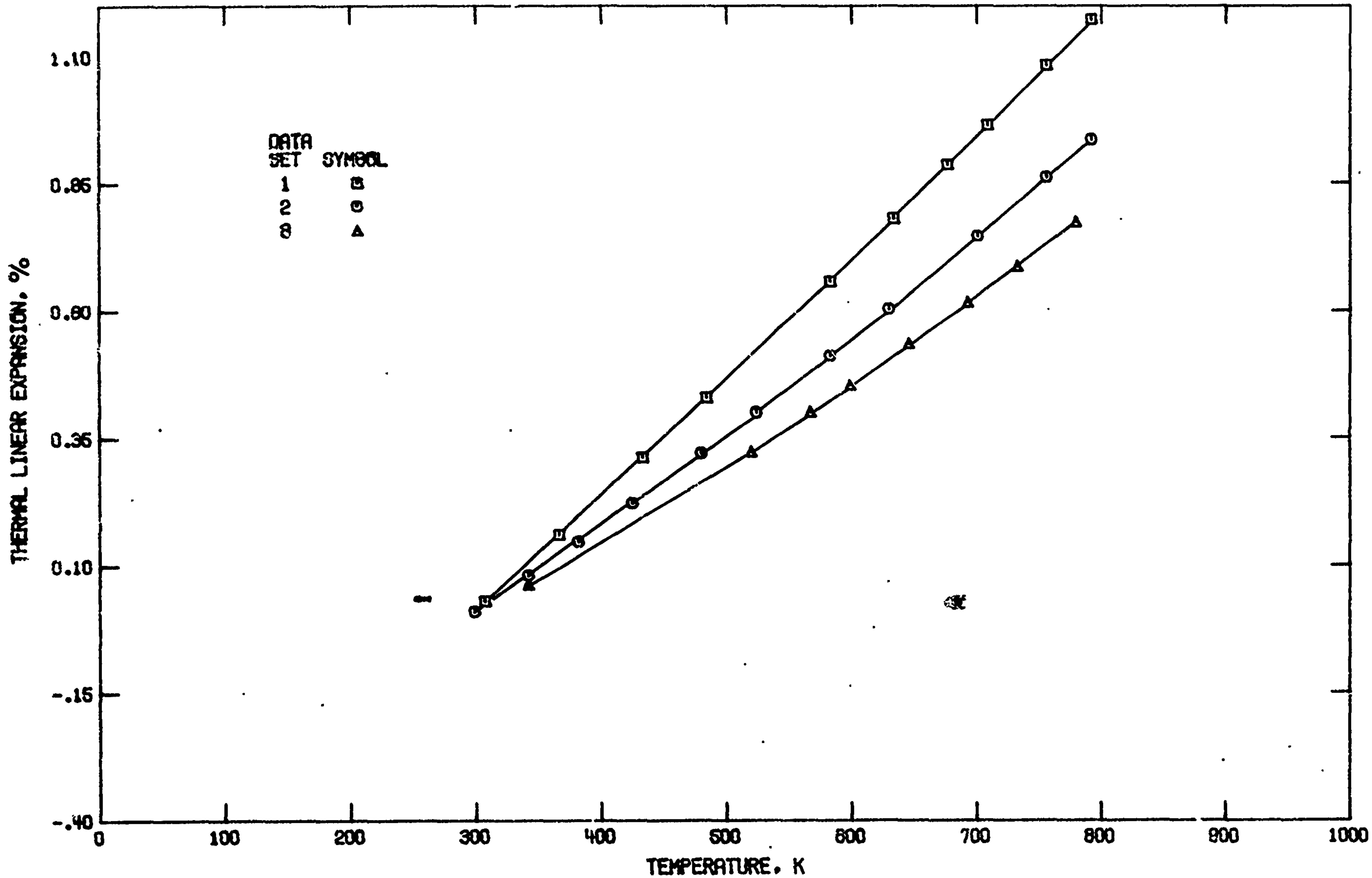

FIGURE 6. THERMAL LINEAR EXPANSION OF KH18N10T FIBER, AD1 ALUMINUM MATRIX COMPOSITE.

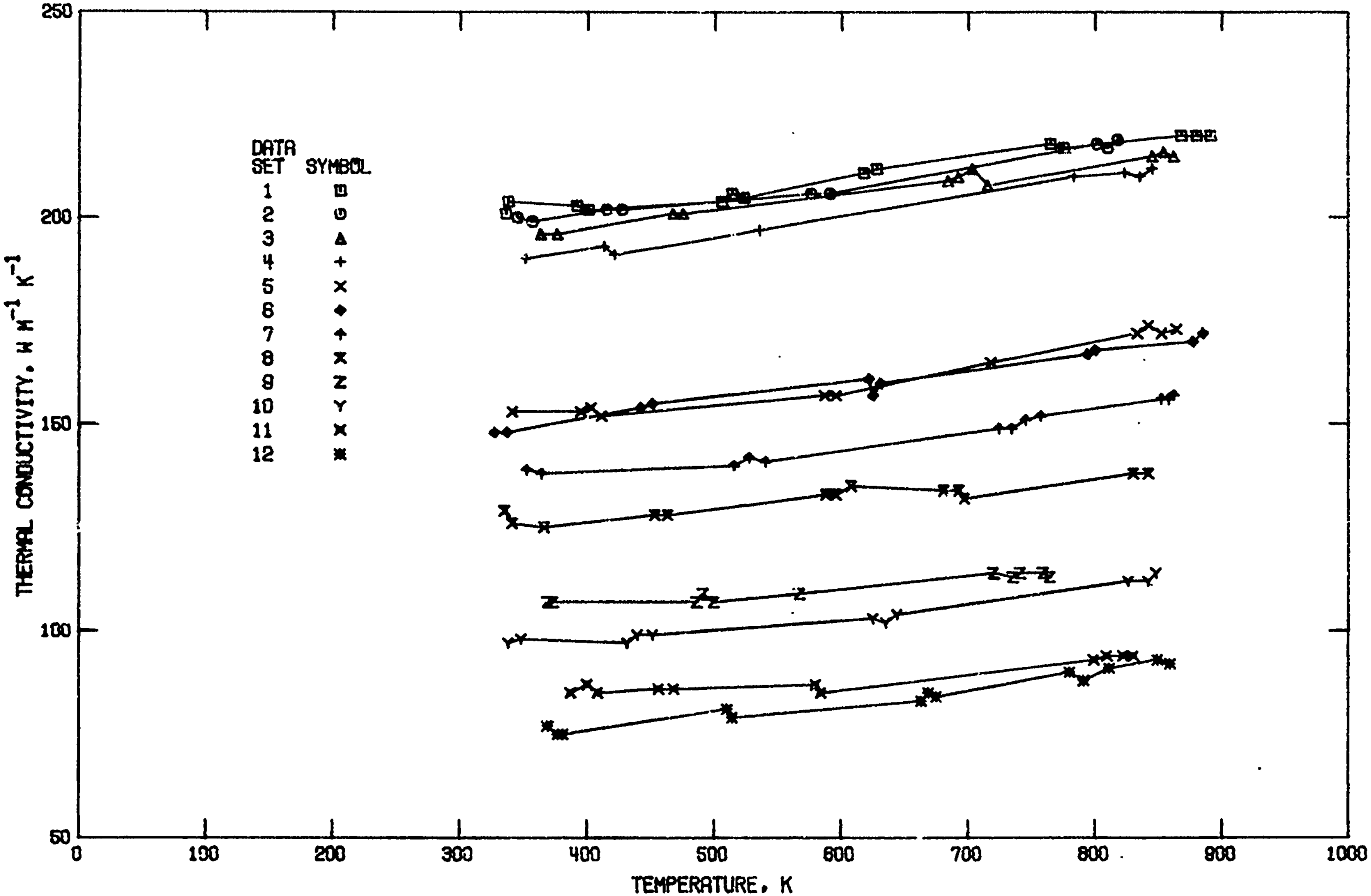

FIGURE 7. THERMAL CONDUCTIVITY OF KH18N10T FIBER, AD1 ALUMINUM MATRIX COMPOSITE.

1.4. QUARTZ FIBER, ALUMINUM MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Salibekov et al. [1] reported a value of $0.55 \times 10^{-6}\ K^{-1}$ for the instantaneous coefficient of thermal expansion at room temperature for a composite containing 70 volume % aluminum matrix.

REFERENCE

1. Salibekov, S.E., Portnoi, K.I., and Chubarov, V.M., High Temp., 10(4), 702-6, 1972.

TABLE 5. DATA ON THE THERMAL LINEAR EXPANSION OF QUARTZ FIBER, ALUMINUM MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	→	→	Quartz fibers (70 volume %) aluminum matrix composites are obtained by steeping the fibers in liquid aluminum under pressure; test specimen 30 x 4 x 3 mm plates; heated in argon atmosphere at 3 deg. min^{-1}, accuracy ±5%, dilatometry. Aluminum matrix undergoes plastic flow right from room temperature. Measurement direction not reported, a single value for instantaneous coefficient of thermal expansion of 0.55 x $10^{-6}K^{-1}$ at room temperature is reported.	Salibekov, S. E., Portnoi, K. I., and Chubarov, V. M., 1972

1.5. U8A STEEL FIBER, AD1 ALUMINUM MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Karpinos et al. [1] reported thermal expansion data for AD1 aluminum reinforced with 9 and 20 volume percent U8A steel (Russian equivalent of AISI W 1 steel) fibers.. Introduction of fibers into the matrix and increasing its concentration causes the coefficient of thermal expansion to decrease monotonically. Karpinos et al. [1] stated that the angle between the fiber direction in a specimen and the specimen's longitudinal axis strongly affects the coefficient of thermal expansion.

REFERENCE

1. Karpinos, D.M., Kadyrov, V.Kh., Klimenko, V.S., Fefer, V.Ya., and Miroshnikova, T.K., Sov. Powder Met. Metal. Ceram.(4), 301-3, 1974.

TABLE 6. DATA ON THE THERMAL LINEAR EXPANSION OF U8A STEEL FIBER, AD1 ALUMINUM MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	189	-0.193	AD1 aluminum base composite reinforced with U8A steel fiber; composites prepared by technique of elevated temperature densification of packs composed of alternating matrix foil and reinforcing fiber layers, 9 vol. % U8A steel fibers; thermal expansion of composite was measured on 4-mm square by 60 mm long prismatic specimens cut from densified blanks oriented parallel to the direction of fiber orientation; volume fraction of fibers determined on micrographs of specimen cross sections; thermal expansion measured on chevenard type dilatometer in argon atmosphere; heating rate 2° C min^{-1}; values calculated by integrating graphically reported values of instantaneous coefficient.	Karpinos, D. M., Kadyrov, V. Kh., Klimenko, V. S., Fefer, V. Ya., and Miroshnikova, T. K., 1974
	228	-0.124		
	275	-0.036		
	334	0.081		
	378	0.172		
	429	0.282		
	539	0.532		
	591	0.658		
	646	0.795		
	685	0.894		
	733	1.018		
	784	1.153		
2 [1]	236	-0.059	Similar to the above except 20 volume % U8A steel fibers.	Karpinos, D. M., et al., 1974
	287	-0.007		
	334	0.046		
	382	0.105		
	437	0.179		
	492	0.259		

TABLE 6. DATA ON THE THERMAL LINEAR EXPANSION OF USA STEEL FIBER, AD1 ALUMINUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
2 (cont.) [1]	591 638 685 733 788	0.419 0.503 0.589 0.679 0.786		
3 [1]	300 400	0.099 * 0.151 *	Similar to the above except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 15 degrees.	Karpinos, D. M., et al., 1974
4 [1]	300 400	0.011 * 0.167 *	Similar to the above except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 35 degrees.	Karpinos, D. M., et al., 1974
5 [1]	300 400	0.011 * 0.174 *	Similar to the above except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 45 degrees.	Karpinos, D. M., et al., 1974
6 [1]	300 400	0.012 * 0.183 *	Similar to the above except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 60 degrees.	Karpinos, D. M., et al., 1974
7 [1]	300 400	0.012 * 0.188 *	Similar to the above except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 90 degrees.	Karpinos, D. M., et al.. 1974

*Not shown in figure.

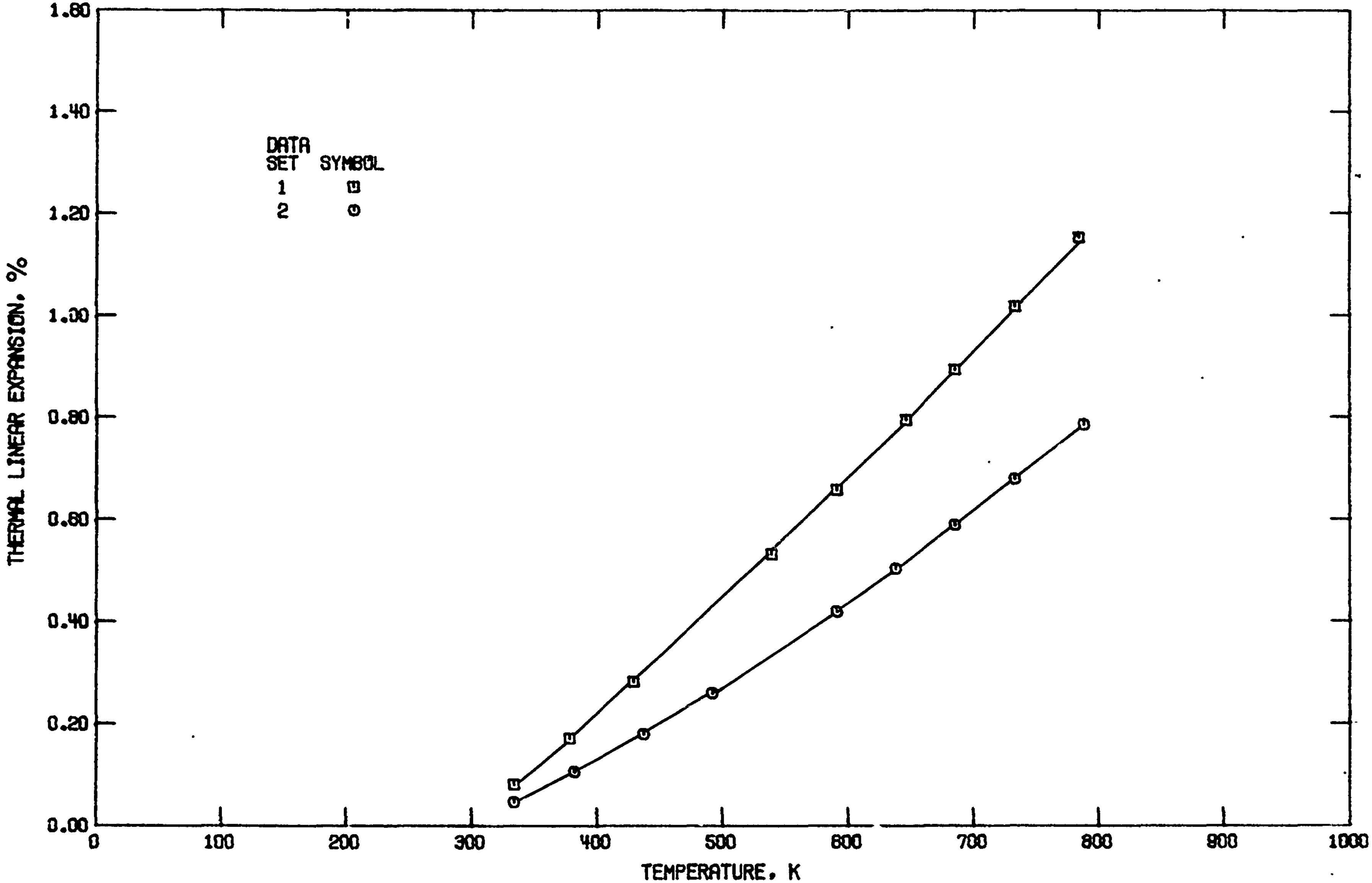

FIGURE 8. THERMAL LINEAR EXPANSION OF U8A STEEL FIBER, AD1 ALUMINUM MATRIX COMPOSITE.

1.6. GRAPHITE FIBER, ALUMINUM-201 MATRIX COMPOSITE

THERMAL EXPANSION

Armstrong and Ellison [1] reported 12 data sets for the thermal linear expansion of 24 and 29 volume percent "GY 70" graphite fiber in an aluminum-201 matrix. The expansion studies were carried out by the Properties Research Laboratory (PRL) of Purdue University and Fiber Materials Inc. (FMI). Measurements were conducted on composites which were diffusion-bonded at pressures from 3000 to 4000 psig. The average longitudinal mean coefficient of thermal expansion for 29 volume percent fiber ranged from 5.32×10^{-6} °C^{-1} (−157°C to 22°C) from FMI measurements and 6.41×10^{-6} °C^{-1} (−157°C to 22°C) from PRL measurements to 6.10×10^{-6} °C^{-1} (22°C to 121°C) from FMI measurements and 5.22×10^{-6} °C^{-1} (22°C to 121°C) from PRL measurements. Higher expansion was reported for a composite with 24 volume percent fiber. Armstrong and Ellison [1] also reported data for a specimen that was thermally cycled 20 and 1000 times.

THERMAL CONDUCTIVITY

There is one reference [1] in which the thermal conductivity of a graphite fiber (GY 70) aluminum-201 matrix composite was reported. The specimens were panels made of aligned, monolayer fibers coated with aluminum-201. Before being consolidated into panels, the coated fibers were aligned and cladded in aluminum-2024 foils. For some of the panels, the fibers are encapsulated in aluminum-2024 foils. The fiber contents of these composites varied from 24 to 29 volume percent. Thermal conductivity values

for heat flow both in the perpendicular and the parallel directions (to the fibers) were reported. Values in the parallel direction are about two times of those in the perpendicular direction at liquid nitrogen temperature, and increase to about 2½ times at 450 K.

ELECTRICAL RESISTIVITY

Only one reference contains data on the electrical resistivity of aluminum-201 matrix with 24, 27.75, and 29 volume percent graphite fiber for temperatures from 116 to 394 K [1].

REFERENCE

1. Armstrong, H.H. and Ellison, A.M., U.S. Air Force Rept. AFML-TR-79-4007, 213 pp., 1979.

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %; Thermal Conductivity, λ, W m^{-1} K^{-1}; Electrical Resistivity, ρ, 10^{-8} Ω m]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	117	-0.094	GY 70 graphite fiber and aluminum alloy 201 matrix; 29 volume % fiber content; eight-end collimated tows of graphite fiber coated with thin layer (100-200 angstrom) of titanium boride for promotion of wetting with and protection against molten aluminum; tows were drawn through a molten aluminum alloy 201 bath; the coated wires had 37 volume % fiber; fibers were aligned in monolayer panels cladded with 0.004 inch thick aluminum alloy 2024 foils; panels were "off-gassed" in vacuum and diffusion bonded at 1000-1060°F and a pressure of 4000 psig; panels were lightly clamped between flats of 0.125 inch thick aluminum and slowly immersed in liquid nitrogen for three minutes, allowed to warm in room ambient for five minutes; this cycle was repeated thrice; measurements carried out by Properties Research Laboratory of Purdue Univ.; measurements in the longitudinal direction; zero point correction is 0.002% data extracted from figure.	Armstrong, H. H. and Ellison, A. M., 1979
	138	-0.086		
	156	-0.078		
	174	-0.069		
	189	-0.061		
	204	-0.053		
	219	-0.045		
	232	-0.037		
	246	-0.028		
	269	-0.020		
	272	-0.012		
	284	-0.004		
	297	0.002		
	310	0.011		
	320	0.018		
	330	0.024		
	340	0.030		
	350	0.036		
	360	0.042		
	370	0.048		
	380	0.055		
	390	0.061		
	400	0.067		

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
2 [1]	117	-0.086	Similar to the above except diffusion bonded at 3000 psig; data extracted from figure.	Armstrong, H. H. and Ellison, A. M., 1979
	138	-0.080		
	156	-0.073		
	174	-0.067		
	189	-0.059		
	204	-0.052		
	219	-0.045		
	232	-0.037		
	246	-0.029		
	269	-0.021		
	272	-0.013		
	284	-0.004		
	297	0.002		
	310	0.011		
	320	0.017		
	330	0.023		
	340	0.028		
	352	0.034		
	360	0.039		
	370	0.045		
	380	0.050		
	390	0.055		
	400	0.061		
3 [1]	117	-0.094	Similar to the above except diffusion bonded at 3500 psig; data extracted from figure.	Armstrong, H. H. and Ellison, A. M., 1979
	138	-0.086		
	156	-0.078		
	174	-0.070		
	189	-0.062		

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
3 (cont.) [1]	204	-0.053		
	219	-0.045		
	232	-0.038		
	246	-0.028		
	269	-0.020		
	272	-0.012		
	284	-0.004		
	297	0.002		
	310	0.012		
	320	0.019		
	330	0.025		
	340	0.031		
	350	0.038		
	360	0.044		
	370	0.051		
	380	0.057		
	390	0.063		
	400	0.069		
4 [1]	117	-0.147	Similar to the above except fibers were encapsulated with 0.002 inch thick aluminum alloy 2024 foil; aligned in monolayer panels; cladded in 0.002 inch thick aluminum alloy 2024 foils and diffusion bonded at 3000 psig; fiber volume 24 %; data extracted from figure.	Armstrong, H. H. and Ellison, A. M., 1979
	138	-0.125		
	156	-0.113		
	174	-0.097		
	189	-0.086		
	204	-0.074		
	219	-0.062		
	232	-0.050		
	246	-0.039		
	269	-0.027		

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
4 (cont.) [1]	272	-0.016		
	284	-0.005		
	297	0.003		
	310	0.016		
	320	0.024		
	330	0.032		
	340	0.040		
	350	0.048		
	360	0.057		
	370	0.065		
	380	0.073		
	390	0.081		
	400	0.089		
5 [1]	117	-0.133	Similar to the above except diffusion bonded at 3500 psig; data extracted from figure.	Armstrong, H. H. and Ellison, A. M., 1979
	138	-0.121		
	156	-0.110		
	174	-0.097		
	189	-0.085		
	204	-0.074		
	219	-0.063		
	232	-0.051		
	246	-0.039		
	269	-0.028		
	272	-0.017		
	284	-0.005		
	297	0.003		
	310	0.013		
	320	0.020		

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
5 (cont.) [1]	330	0.028		
	340	0.036		
	350	0.043		
	360	0.051		
	370	0.059		
	380	0.067		
	390	0.075		
	400	0.083		
6 [1]	117	−0.130	Similar to the above except diffusion bonded at 4000 psig; data extracted from figure.	Armstrong, H. H. and Ellison, A. M., 1979
	133	−0.117		
	156	−0.107		
	174	−0.097		
	189	−0.085		
	204	−0.074		
	219	−0.063		
	232	−0.051		
	246	−0.039		
	269	−0.028		
	272	−0.017		
	284	−0.005		
	297	0.003		
	310	0.014		
	320	0.021		
	330	0.029		
	340	0.036		
	350	0.043		
	360	0.051		
	370	0.058		

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
6 (cont.) [1]	330 390 400	0.066 0.073 0.080		
7 [1]	116 295 394	-0.095 0.001 0.062	Average value of the mean coefficient of thermal expansion for composites made under different condition described in data sets 1-6; 29 volume % fiber volume; average of three runs by Fiber Materials Inc.; data calculated from the tabulated values of mean coefficient of thermal expansion.	Armstrong, H. H. and Ellison, A. M., 1979
8 [1]	116 295 394	-0.133 0.002 0.090	Similar to the above except 24 volume % fiber; data calculated from tabulated values of mean coefficient of thermal expansion.	Armstrong, H. H. and Ellison, A. M., 1979
9 [1]	116 295 394	-0.131 0.002 0.085	Similar to the one reported in data set 4 except specimen thermally cycled from liquid nitrogen temperature to room temperature 20 times: 23.7 volume % fiber (24 volume % for uncycled specimen); values calculated from tabulated values of mean coefficient of thermal expansion.	Armstrong, H. H. and Ellison, A. M., 1979

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
10 [1]	116 295 394	-0.142 0.002 0.076	Similar to the above except specimen thermally cycled over 1000 times; 23.3 volume % fiber (24 volume % for uncycled specimen); values calculated from tabulated values of mean coefficient of thermal expansion.	Armstrong, H. H. and Ellison, A. M.,1979
11 [1]	116 295 394	-0.088 0.001 0.048	Specimen made eight-end GY70/Al 201 wire produced by MCI; consolidated with 4 mil cladding on each side at 3500 psi and 1040°F for 30 minutes; quenched after consolidation; measurement in the longitudinal direction by Fiber Materials Incorporated on eight specimens; average values of the mean coefficient of thermal expansion are reported; 28.6 volume % fiber; values calculated from tabulated values of mean coefficient of thermal expansion.	Armstrong, H. H. and Ellison, A. M.,1979
12 [1]	116 295 394	-0.076 0.001 0.047	Similar to the above except 28.5 volume % fiber; average values of the mean coefficient of thermal expansion on two specimen; measurements by Lockheed Missiles and Space Co., Inc.; values calculated from tabulated mean coefficient of thermal expansion.	Armstrong, H. H. and Ellison, A. M.,1979

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY	
1 [1]	91	22.5	GY 70 fiber, aluminum 201 matrix composite, fiber volume 29%; eight-end collimated tows of graphite fiber coated with thin layer (100-200 A) of titanium boride for promotion of wetting with and protection against molten aluminum; the tows were drawn through a molten aluminum 201 bath; the coated wires had fiber volume content ~37%: the wires were aligned in monolayer panels, cladded with 0.004 inch thick aluminum 2024 foils; the panels were "off-gassed in vacuum and diffusion bonded at 1000 - 1060°F and a pressure of 4000 psig; the panels were then lightly clamped between flat plates of 0.125 in thick aluminum and slowly immersed in liquid nitrogen for three minutes, allowed to warm in room ambient air for 5 minutes; the cycle was repeated for a total of 3 cycles; specimen nominal dimensions 0.03 x 0.375 x 2.70 in^3; measured by the Kohlrausch method with fiber direction perpendicular to the longitudinal axis.	Armstrong, H. H. and Ellison, A. M., 1979
	106	26.1		
	122	28.9		
	138	32.2		
	158	35.4		
	172	38.0		
	186	40.5		
	214	44.7		
	227	46.2		
	249	48.6		
	255	49.4		
	273	52.2		
	313	60.9		
	333	62.5		
	367	63.6		
	427	71.3		

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
2 [1]	96	27.8	Similar to the above except diffusion bonded at a pressure of 3000 psig.	Armstrong, H. H. and Ellison, A. M., 1979
	116	32.7		
	141	38.1		
	167	43.0		
	197	47.4		
	230	52.6		
	323	61.2		
	336	63.5		
	359	66.3		
	384	68.7		
	415	71.5		
	451	73.1		
3 [1]	91	27.4	Similar to the above except diffusion bonded at a pressure of 3500 psig.	Armstrong, H. H. and Ellison, A. M., 1979
	99	28.1		
	142	36.9		
	177	43.6		
	209	49.3		
	311	63.7		
	621	64.6		
	337	67.1		
	376	71.6		
	412	74.8		
	474	77.8		
4 [1]	91	31.2	Similar to the above except the wires were encapsulated with 0.002 in thick aluminum 2024 foil, aligned in monolayer panels, cladded 0.002 in	Armstrong, H. H. and Ellison, A. M., 1979
	102	34.5		
	117	38.1		
	149	44.1		

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
4 (cont.) [1]	186	50.1	thick aluminum 2024 foils and diffusion bonded at 3000 psig; fiber volume 24%.	
	241	61.3		
	308	70.1		
	315	71.5		
	339	75.1		
	351	76.7		
	368	79.2		
	389	81.8		
5 [1]	89	31.5	Similar to the above except diffusion bonded at a pressure of 3500 psig.	Armstrong, H. H. and Ellison, A. M., 1979
	108	35.6		
	125	40.2		
	147	46.4		
	178	53.3		
	217	60.6		
	232	63.2		
	255	66.8		
	306	75.5		
	316	75.9		
	333	76.9		
	350	78.1		
	365	79.8		
6 [1]	93	34.5	Similar to the above except diffusion bonded at 4000 psig.	Armstrong, H. H. and Ellison, A. M., 1979
	110	38.7		
	183	53.9		
	221	66.0		
	248	69.9		
	306	73.5		

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
6 (cont.) [1]	314	74.6		
	326	76.4		
	340	78.6		
	352	80.5		
	370	82.0		
	388	84.7		
7 [1]	116	47.9	Similar to the above, thermally cycled between liquid nitrogen and room temperatures 20 times; fiber volume 23.1%.	Armstrong, H. H. and Ellison, A. M., 1979
	293	67.0		
	394	78.0		
8 [1]	116	47.9	Similar to the above except consolidated at 3500 psig and 1040°F for 20 minutes, plate quenched and mechnically surface honed; fiber volume 24.0%; measured by a guarded longitudinal heat flow method, with heat flow perpendicular to the fiber direction; value from table.	Armstrong, H. H. and Ellison, A. M., 1979
	293	65.0		
	394	73.0		
9 [1]	293	76. *	Similar to the above, thermally cycled 1000+ times; fiber volume 23.3%.	Armstrong, H. H. and Ellison, A. M., 1979
10 [1]	94	31.2	Similar to the above except not thermally cycled; fiber volume 27.1%; measured either by the Kohlrausch method or the guarded longitudinal	Armstrong, H. H. and Ellison, A. M., 1979
	104	35.9		
	121	39.6		
	152	47.2		

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
10 (cont.) [1]	191	54.9	heat flow method; fiber direction perpendicular to specimen axis.	
	225	60.7		
	243	63.8		
	278	69.4		
	309	71.7		
	320	72.8		
	327	74.4		
	346	76.7		
	366	79.1		
	386	80.7		
	418	82.3		
11 [1]	93	32.0	Similar to the above except fiber volume 28.2%.	Armstrong, H. H. and Ellison, A. M., 1979
	111	36.2		
	129	40.4		
	152	44.6		
	180	50.7		
	199	53.8		
	217	57.0		
	233	58.6		
	250	60.4		
	274	63.6		
	311	70.4		
	321	72.0		
	333	73.3		
	368	77.8		
	389	79.6		
	426	81.8		

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
12 [1]	88	29.1	Similar to the above.	Armstrong, H. H. and Ellison, A. M., 1979
	107	33.6		
	126	38.3		
	159	45.7		
	189	51.5		
	212	55.9		
	242	61.2		
	280	67.0		
	317	69.9		
	328	72.0		
	344	74.4		
	363	75.7		
	385	78.9		
	443	82.3		
13 [1]	78	28.3	Similar to the above except fiber volume 28.1%.	Armstrong, H. H. and Ellison, A. M., 1979
	90	32.2		
	107	36.2		
	124	40.7		
	146	44.6		
	176	50.4		
	195	54.1		
	243	62.2		
	278	65.4		
	308	68.1		
	319	69.6		
	330	71.2		
	344	73.1		
	362	75.2		
	383	77.5		
	416	79.9		

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
14 [1]	77	46.4	Similar to the above except fiber volume 28.4% and fiber direction parallel to the specimen axis.	Armstrong, H. H. and Ellison, A. M., 1979
	85	49.8		
	102	57.7		
	133	70.1		
	152	76.4		
	180	91.9		
	201	101.3		
	240	118.4		
	303	134.2		
	308	136.8		
	320	140.5		
	329	143.2		
	337	145.0		
	347	147.6		
	359	150.5		
	370	153.2		
	381	155.5		
	397	157.4		
15 [1]	82	47.2	Similar to the above except fiber volume 28.6%.	Armstrong, H. H. and Ellison, A. M., 1979
	98	57.5		
	122	69.3		
	147	79.5		
	161	91.6		
	184	101.1		
	193	106.9		
	231	122.4		
	303	141.0		
	307	143.1		

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
15 (cont.)	314	144.7		
[1]	322	147.1		
	327	149.2		
	337	152.9		
	348	155.8		
	361	158.7		
	373	161.8		
	388	164.4		
	400	166.8		
16	188	51.4	Specimen identified as No. NRT-6; no other details given.	Armstrong, H. H. and Ellison, A. M., 1979
[1]	212	59.5		
	237	50.3		
	245	67.1		
	283	71.6		
	324	55.7		
	353	80.6		
	367	75.5		
	386	51.5		
	T	ρ	ELECTRICAL RESISTIVITY	
1	116	10.2	Graphite reinforced aluminum composite was produced by diffusion bonding and clad with aluminum foils, cladding thickness is 0.004 inch; fiber volume 29%; consolidation pressure 3000 to 4000 psi at 1040°F; quenched 3 times in liquid nitrogen.	Armstrong, H. H., and Ellison, A. M., 1978
[1]	295	14.87		
	394	17.43		

TABLE 7. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF GRAPHITE FIBERS, ALUMINUM-201 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	ρ	ELECTRICAL RESISTIVITY (cont.)	
2 [1]	116 295 394	7.7 11.47 13.5	graphite reinforced aluminum composite specimen was produced by diffusion bonding and clad with aluminum foils, encapsulated with 0.007 inch foil with addition 0.002 inch foil cladding; fiber volume 24%; consolidated pressure 3000 to 4000 psi at 1040°F; quenched 3 times in liquid nitrogen.	Armstrong, H. H. and Ellison, A. M., 1979
3 [1]	116 295 394	7.6 12.1 14.5	GH70/201 MMC transerse fiber specimen; 0.002 inch cladding thickness; fiber volume 27.75%.	Armstrong, H. H. and ellison, A. M., 1979
4 [1]	295	13.1	GH70/201 MMC transverse fiber specimen; 0.004 inch cladding thickness; 29% fiber volume.	Armstrong, H. H. and Ellison, A. M., 1979
5 [1]	295	7.8	GY70/201 Al MMC; 4 mil cladding, 29% fiber volume, 3500 psi consolidation at 1040°F for 20 minutes; longitudinal fiber.	Armstrong, H. H. and Ellison, A. M., 1979
6 [1]	295	9.8	GH70/201 Al MMC; 4 mil cladding, 29% fiber volume, 3500 psi consolidation at 1040°F for 20 minutes, transverse fiber.	Armstrong, H. H. and Ellison, A. M., 1979

*Not shown in figure.

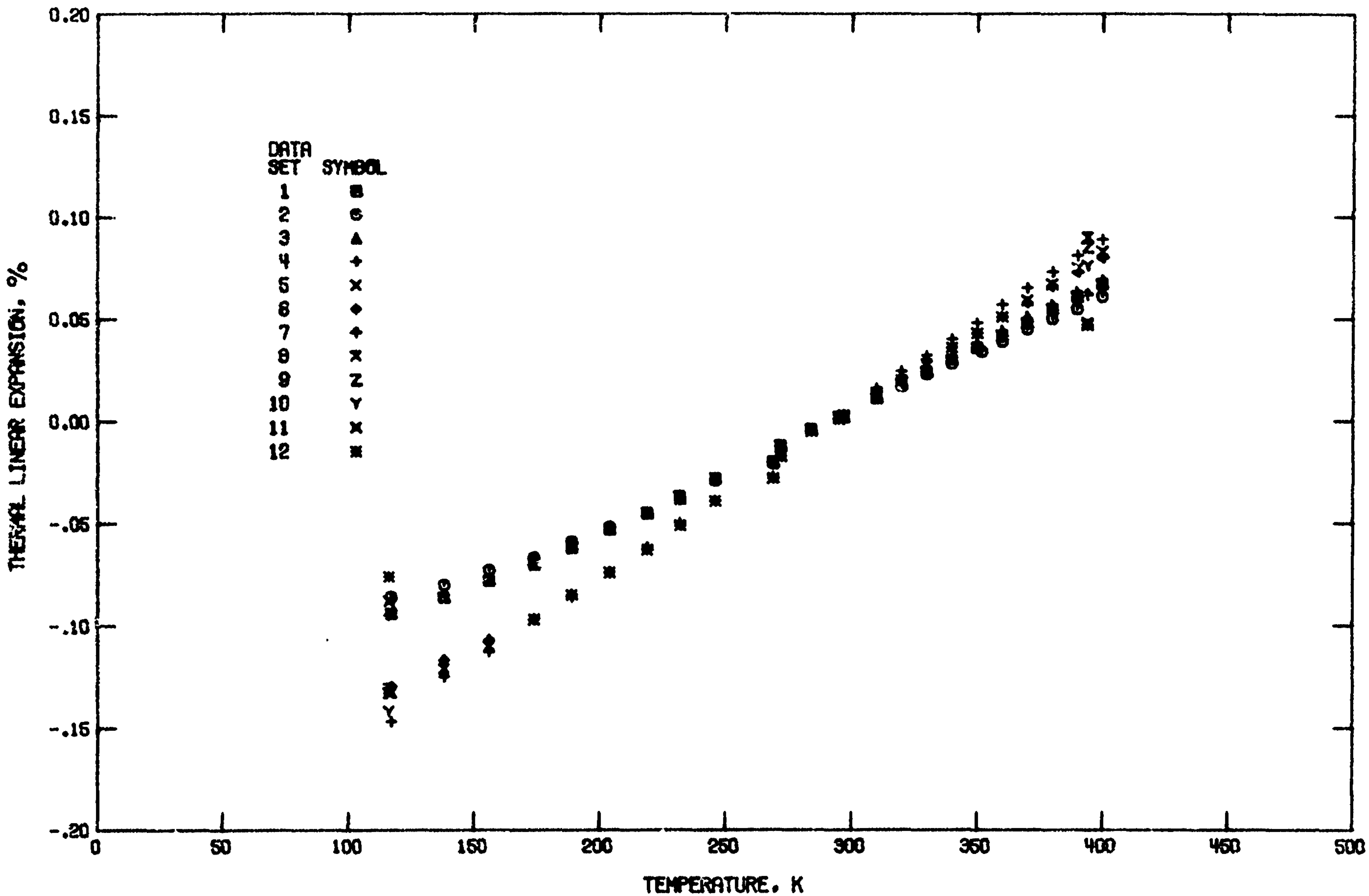

FIGURE 9. THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, ALUMINUM-201 MATRIX COMPOSITE.

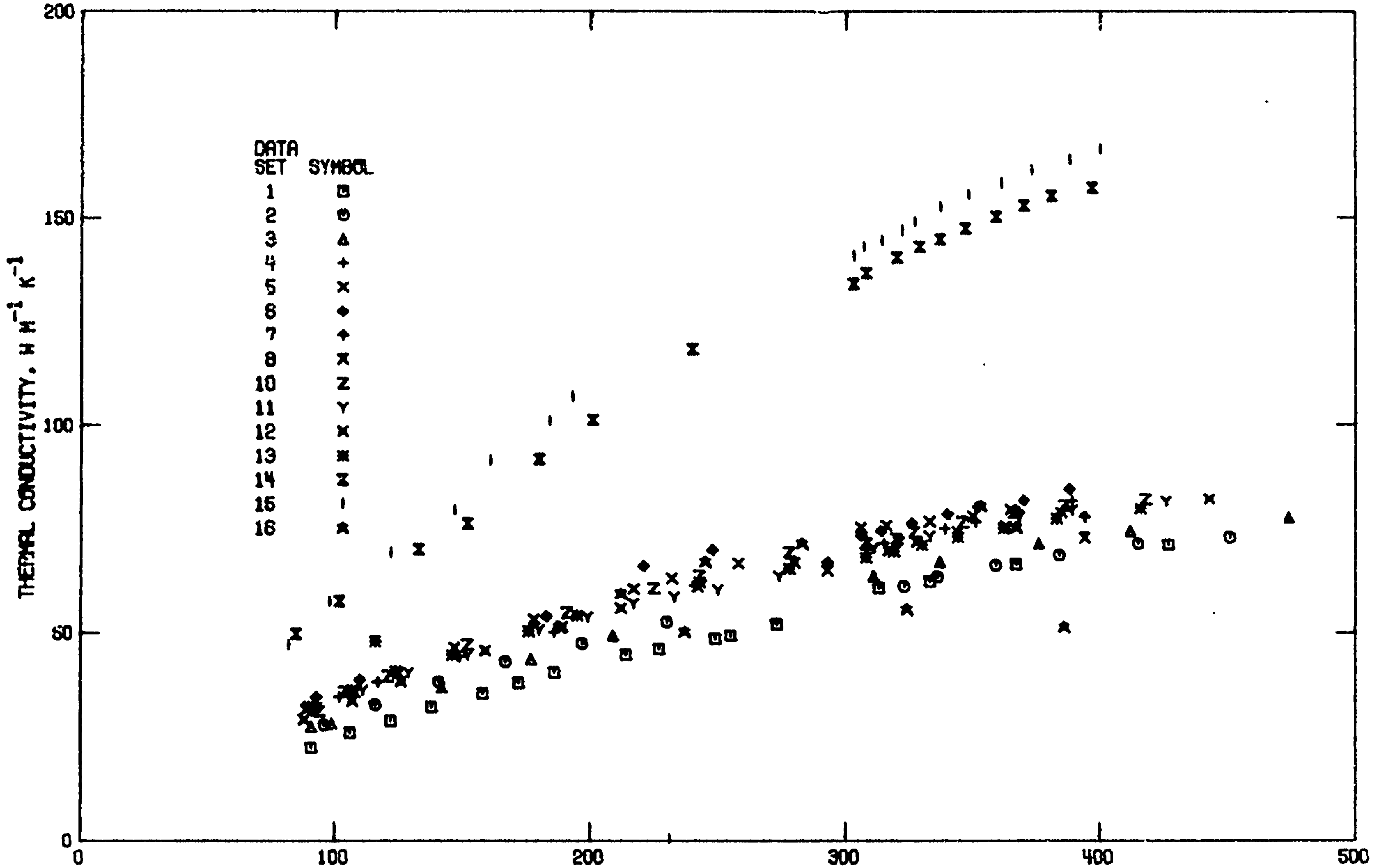

FIGURE 10. THERMAL CONDUCTIVITY OF GRAPHITE FIBER, ALUMINUM-201 MATRIX COMPOSITE.

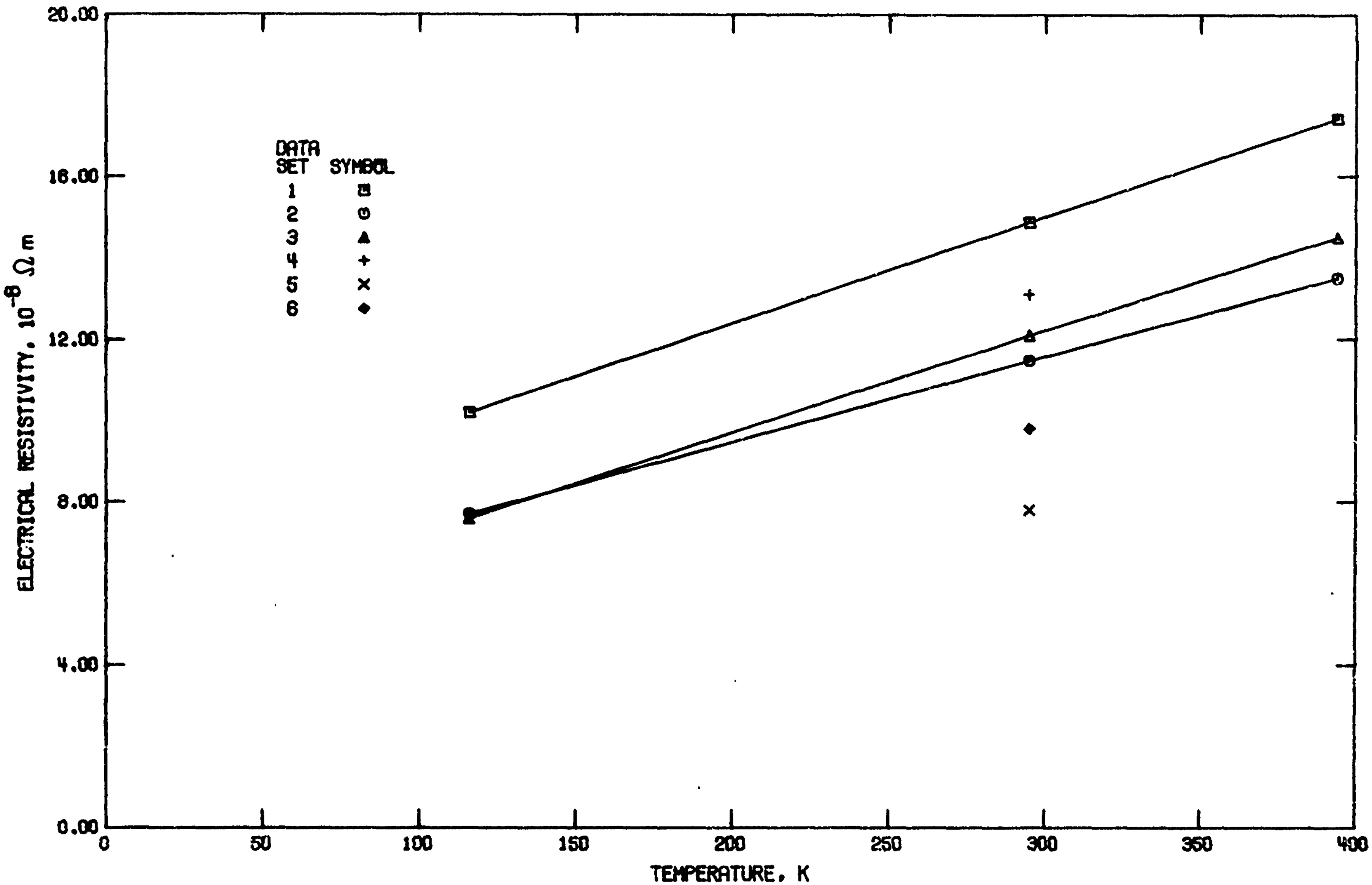

FIGURE 11. ELECTRICAL RESISTIVITY OF GRAPHITE FIBER, ALUMINUM-201 MATRIX COMPOSITE.

1.7. BORSIC FIBER, ALUMINUM-1100 MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Kreider and Patarini [1] reported thermal expansion for diffusion-bonded composites containing 24, 28, and 50 volume percent Borsic fibers (boron fibers coated with silicon carbide) in both the longitudinal and transverse directions. Longitudinal percent thermal expansion decreased from 0.188 for the 24 volume percent composite to 0.129 for the 50 volume percent composite near 570 K. Transverse expansion also showed a similar decreasing trend. The expansion pattern was fairly uniform.

REFERENCE

1. Kreider, K.G. and Patarini, V.M., Trans. Met. Soc. AIME, 1(12), 3431-5, 1970.

TABLE 8. DATA ON THE THERMAL LINEAR EXPANSION OF BORSIC FIBERS, ALUMINUM-1100 MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	297	0.001	Composites were hot-press diffusion bonded at 20 - 40° C below their matrix solidus temperature and 5000 psi from plasma sprayed monolayer tapes, slow cool was used to minimize residual stresses and yielded an "annealed" structure; measurements with quartz tube dilatometer; 24 volume % borsic fibers; axial thermal expansion; data extracted from figure.	Kreider, K. G., and Patarini, V. M., 1970
	325	0.025		
	340	0.039		
	354	0.055		
	364	0.065		
	374	0.074		
	392	0.086		
	424	0.102		
	452	0.114		
	473	0.126		
	501	0.147		
	522	0.160		
	545	0.174		
	569	0.188		
2 [1]	299	0.001	Composites were hot-press diffusion bonded at 20 - 40° C below their matrix solidus temperature and 5000 psi from plasma sprayed monolayer tapes, slow cool was used to minimize residual stresses and yielded an "annealed" structure; measurements with quartz tube dilatometer; 28 volume % borsic fibers; axial thermal expansion, data extracted from figure.	Kreider, K. G. and Patarini, V. M., 1970
	324	0.015 *		
	345	0.033		
	360	0.044		
	374	0.053		
	400	0.067		
	423	0.079		
	449	0.093		
	473	0.104		
	498	0.117		
	523	0.130		
	545	0.139		
	569	0.152		

TABLE 8. DATA ON THE THERMAL LINEAR EXPANSION OF BORSIC FIBERS, ALUMINUM-1100 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
3 [1]	301	0.001	Composites were hot-press diffusion bonded at 20 - 40° C below their matrix solidus temperature and 5000 psi from plasma sprayed monolayer tapes, slow cool was used to minimize residual stresses and yielded an "annealed" structure; measurements with quartz tube dilatometer; 50 volume % borsic fibers; axial thermal expansion, data extracted from figure.	Kreider, K. G. and Patarini, V. M., 1970
	324	0.010		
	373	0.038		
	400	0.049		
	423	0.056		
	445	0.068		
	457	0.076		
	473	0.083		
	502	0.094		
	523	0.104		
	543	0.117		
	570	0.129		
4 [1]	289	-0.001	Composites were hot-press diffusion bonded at 20 - 40° C below their matrix solidus temperature and 5000 psi from plasma sprayed monolayer tapes, slow cool was used to minimize residual stresses and yielded an "annealed" structure; measurements with quartz tube dilatometer; 24 volume % borsic fibers; transverse expansion, data extracted from figure.	Kreider, K. G. and Patarini, V. M., 1970
	323	0.055 *		
	373	0.158		
	423	0.281 *		
	473	0.410		
	523	0.545		
	570	0.672		
5 [1]	290	-0.001 *	Composites were hot-press diffusion bonded at 20 - 40° C below their matrix solidus temperature and 5000 psi from plasma sprayed monolayer	Kreider, K. G. and Patarini, V. M., 1970
	323	0.043		
	372	0.150 *		
	423	0.273		

TABLE 8. DATA ON THE THERMAL LINEAR EXPANSION OF BORSIC FIBERS, ALUMINUM-1100 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
5 (cont.) [1]	473	0.396	tapes, slow cool was used to minimize residual stresses and yielded an "annealed" structure; measurements with quartz tube dilatometer; 28 volume % borsic fibers; transverse thermal expansion, data extracted from figure.	
	522	0.529		
	570	0.687		
6 [1]	290	-0.001 *	Composites were hot-press diffusion bonded at 20 - 40° C below their matrix solidus temperature and 5000 psi from plasma sprayed monolayer tapes, slow cool was used to minimize residual stresses and yielded an "annealed" structure; measurements with quartz tube dilatometer; 50 volume % borsic fibers; transverse expansion, data extracted from figure.	Kreider, K. G. and Patarini, V. M., 1970
	325	0.035		
	372	0.115		
	423	0.211		
	473	0.301		
	522	0.404		
	571	0.508		

*Not shown in figure.

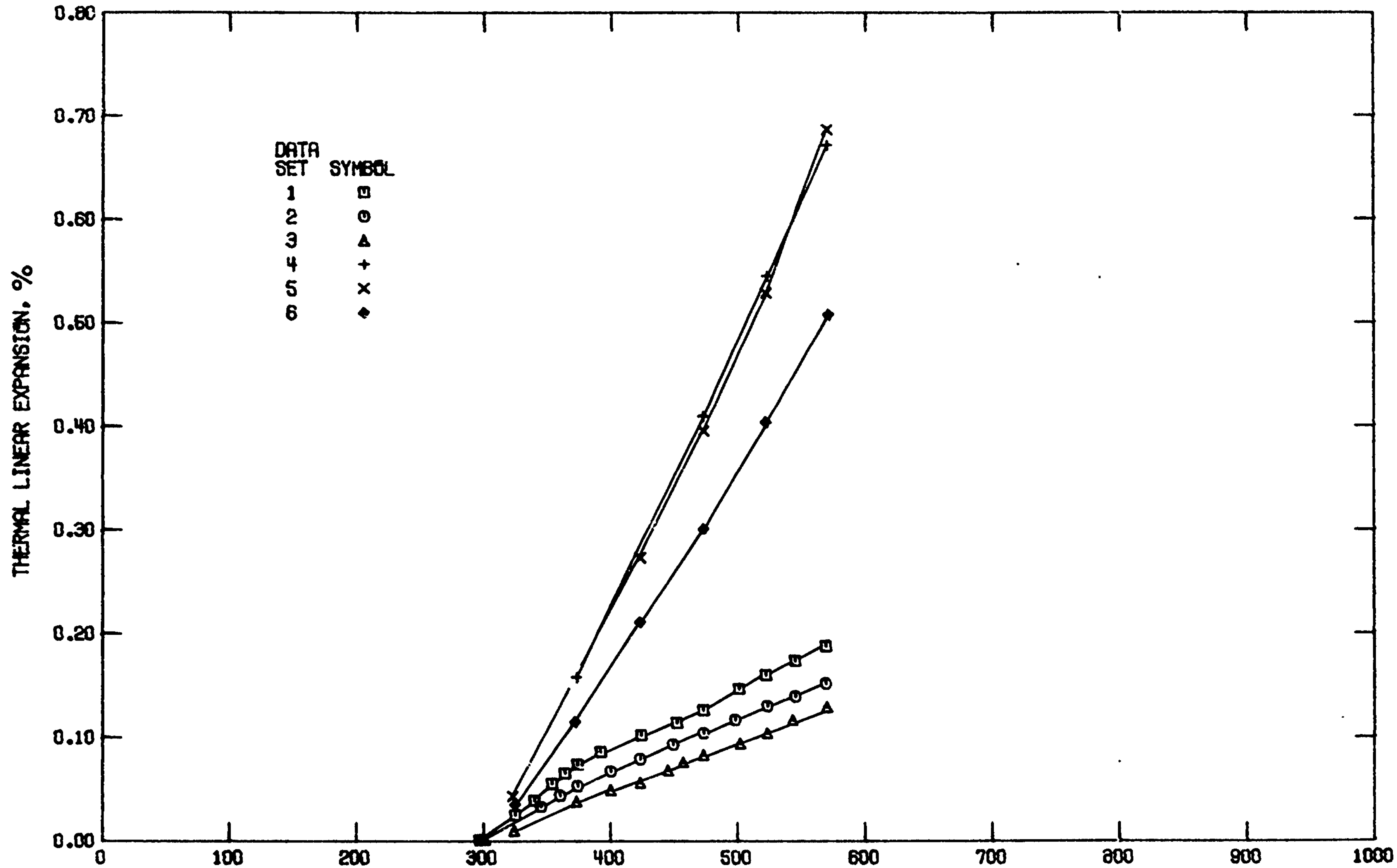

FIGURE 12. THERMAL LINEAR EXPANSION OF BORSIC FIBER, ALUMINUM-1100 MATRIX COMPOSITE.

1.8. 'E' GLASS FIBER, ALUMINUM-2014 MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

There are 24 data sets available for the thermal expansion of parallel oriented 'E' glass (electrically condunting borosilicate glass) fibers in an aluminum-2014 matrix [1-2]. The data are for composites containing 20-40 volume percent glass fibers during several heating and cooling cycles. Lockwood [1] and Ailes [2] reported that these composites exibited a permanent contraction after initial heating and cooling cycles and that this contraction becomes less after succeeding cycles. Lockwood [1] explained this on the basis that glass fibers contract a finite amount at high temperature and slippage of fibers within the metal as a result of internal straining of the metal due to different thermal expansion of the fibers and the matrix. Ailes [2] observed a cumulative contraction of about 0.2 -0.4% after initial heating.

REFERENCES

1. Lockwood, P.A., Owens-Corning Fiberglas Corp. Rept., 164 pp., 1960. [AD-274 530]
2. Ailes, H.B., Glass-Metals Res. Lab., Owens-Corning Fiberglas Corp. Rept., 34pp., 1957. [AD- 153 297]
3. Whitehurst, H.B., Michener, J.W., and Lockwood, P.A., Proc. 6th Sagamore Army Mater. Res. Conf., 248-76, 1960. [AD-233 158]

TABLE 9. DATA ON THE THERMAL LINEAR EXPANSION OF 'E' GLASS FIBER, ALUMINUM-2014 MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	297 345 422 534 652	0.001 0.040 0.109 0.119 0.239	First heating cycle 30 - 40 volume % 'E' glass fiber in an Al-2014 matrix. Fibers are 0.0006" dia., parallel oriented, precoated with Al-1100, 2% Zn + 0.2% Cd. Vacuum injection casting; fibors placed in tube mold open at both ends. One end is connected to vacuum and other is placed in pot of molten metal. As cast. Measurement direction not reported, data reported in data sets 1-10 extracted from table.	Lockwood, P. A., 1960
2 [1]	297 481 841	0.010 0.050 0.240	Similar to above except first cooling cycle.	Lockwood, P. A., 1960
3 [1]	297 805	0.002 0.291	Similar to the above except second heating cycle.	Lockwood, P. A., 1960
4 [1]	297 805	0.002 0.291	Similar to the above except second cooling cycle.	Lockwood, P. A., 1960
5 [1]	294 370 453 524 637 789	0.001 0.051 0.131 0.201 0.231 0.271	Similar to the above except third heating.	Lockwood, P. A., 1960

TABLE 9. DATA ON THE THERMAL LINEAR EXPANSION OF 'E' GLASS FIBER, ALUMINUM-2014 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
6 [1]	294	0.001	Similar to the above except third cooling.	Lockwood, P. A., 1960
	381	0.051		
	485	0.121		
	574	0.181		
	680	0.201		
7 [1]	294	0.001	Similar to the above except fourth heating.	Lockwood, P. A., 1960
	424	0.131		
	627	0.221		
	779	0.241		
8 [1]	294	0.000	Similar to the above except fourth cooling. Zero point correction is -0.020%.	Lockwood, P. A., 1960
	379	0.012		
	567	0.152		
9 [1]	299	0.003	Composite consisted of 'E' glass fibers of 0.0004 in. diameter parallel oriented and 20 volume % fiber precoated with Al-1100 (5% Zn and 1% Cd) alloy; Al-2014 alloy is matrix; composite made using vacuum injection casting; annealed condition; heating cycle; zero point correction is 0.002%. Measurement direction not reported.	Lockwood, P. A., 1960
	367	0.119		
	423	0.259 *		
	481	0.389		
	535	0.538 *		
	584	0.667		
	643	0.781 *		
	701	0.841		
	754	0.863		
	790	0.868		
10 [1]	299	0.005 *	Similar to the above except cooling cycle.	Lookwood, P. A., 1960
	316	0.016		
	367	0.120 *		

TABLE 9. DATA ON THE THERMAL LINEAR EXPANSION OF 'E' GLASS FIBER, ALUMINUM-2014 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
10 (cont.) [1]	424	0.229		
	480	0.341 *		
	534	0.452		
	564	0.486		
	702	0.528		
	754	0.779		
11 [2]	297	0.002	Glass reinforced aluminum made by vacuum injection techniques, 20-30 volume % continuous longitudinally oriented glass fibers in 14S-T6 aluminum matrix made by pulling under vacuum molten 14S aluminum into a mold containing aluminum coated glass fibers; cumulative 0.3 - 0.4 % permanent shrinkage measured upon initial heating from as cast condition to 1000°F for about 24 hours; values reported are for heat treated (annealed) sample and represent equilibrium points, i.e. sample was held at temperature until no further expansion could be detected at that temperature, data reported in data sets 11-22 extracted from table.	Ailes, H. B., 1957
	633	0.587		
	818	0.653		
12 [2]	297	0.003	Similar to the above except second heating cycle.	Ailes, H. B., 1957
	636	0.589		
	822	0.641		

TABLE 9. DATA ON THE THERMAL LINEAR EXPANSION OF 'E' GLASS FIBER, ALUMINUM-2014 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
13 [2]	297	0.003	Similar to the above except third heating cycle.	Ailes, H. B., 1957
	345	0.067		
	427	0.235 *		
	541	0.502		
	638	0.478		
	822	0.626		
14 [2]	297	0.004	Similar to the above except third cooling experiment.	Ailes, H. B., 1957
	389	0.091		
	476	0.229		
	575	0.348		
	688	0.512		
15 [2]	300	0.002	Similar to the above specimen except heating rate 4.5°F min^{-1}.	Ailes, H. B., 1957
	311	0.008		
	366	0.131		
	422	0.151		
	477	0.291		
	533	0.388		
	589	0.410		
	675	0.467		
	700	0.534 *		
	755	0.562		
	772	0.675		
16 [2]	300	0.001	Similar to the above except cooling rate 4.5°F min^{-1}. Zero point correction is -0.037%.	Ailes, H. B., 1957
	422	0.079		
	477	0.274		
	533	0.318		

TABLE 9. DATA ON THE THERMAL LINEAR EXPANSION OF 'E' GLASS FIBER, ALUMINUM-2014 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
16 (cont.) [2]	675	0.337		
	700	0.431		
	755	0.553		
17 [2]	300	0.001	Similar to the above specimen except heating rate 5.5°F min^{-1}.	Ailes, H. B., 1957
	311	0.009		
	366	0.121 *		
	420	0.264		
	477	0.397 *		
	533	0.546		
	589	0.675 *		
	644	0.786		
	700	0.841		
	755	0.875		
	789	0.877		
18 [2]	300	0.002	Similar to the above except cooling rate 5.5°F min^{-1}.	Ailes, H. B., 1957
	383	0.156		
	422	0.224 *		
	477	0.342		
	533	0.458 *		
	564	0.500		
	700	0.543		
	755	0.775		
19 [2]	299	0.001	Similar to the above specimen except heating rate 5.3°F min^{-1}.	Ailes, H. B., 1957
	322	0.039		
	366	0.128 *		
	422	0.261		

TABLE 9. DATA ON THE THERMAL LINEAR EXPANSION OF 'E' GLASS FIBER, ALUMINUM-2014 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
19 (cont.) [2]	477	0.388 *		
	533	0.524		
	589	0.650		
	644	0.719		
	700	0.767		
	755	0.790		
	811	0.778		
20 [2]	299	0.001	Similar to the above except cooling rate 5.3°F min^{-1}.	Ailes, H. B., 1957
	383	0.255		
	422	0.317		
	477	0.431		
	533	0.506 *		
	589	0.576		
	644	0.669		
21 [2]	300	0.001	Similar to the above specimen except heating rate 4.5°F min^{-1}.	Ailes, H. B., 1957
	311	0.008		
	366	0.119		
	422	0.175		
	477	0.349		
	539	0.474		
	589	0.537		
	644	0.575 *		
	700	0.601		
	755	0.615		
	786	0.615		

TABLE 9. DATA ON THE THERMAL LINEAR EXPANSION OF 'E' GLASS FIBER, ALUMINUM-2014 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
22 [2]	300	0.004	Similar to the above except cooling rate 4.5°F min^{-1}; zero point correction -0.005%.	Ailes, H. B., 1957
	455	0.137 *		
	544	0.263		
	589	0.321		
	644	0.365		
	700	0.420		
	755	0.477		
23 [3]	305	0.001	'E' glass fibers 20 volume %, 0.0006 inch in diameter and parallel oriented; 2014 Al matrix composites have been heated several times or normalized at their service temperature before experiments, data extracted from figure.	Whitehurst, H. B., Michener, J. M., and Lockwood, P. A., 1960
	337	0.049		
	365	0.102		
	392	0.151		
	421	0.215		
	446	0.275		
	466	0.335		
	477	0.372		
	499	0.423		
	518	0.461		
	529	0.479		
	555	0.514		
	578	0.534		
	594	0.550		
	622	0.568		
	642	0.575 *		
	664	0.586		
	697	0.598 *		
	725	0.602		
	760	0.610 *		
	785	0.612 *		
	812	0.613		
	829	0.613		

TABLE 9. DATA ON THE THERMAL LINEAR EXPANSION OF 'E' GLASS FIBER, ALUMINUM-2014 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	<u>THERMAL LINEAR EXPANSION</u> (cont.)	
24 [3]	329	0.017	Similar to the above except cooling curve; zero point correction is -0.012%, data extracted from figure.	Whitehurst, H. B., Michener, J. M., and Lockwood, P. A., 1960
	368	0.062		
	421	0.121		
	450	0.155		
	477	0.192		
	503	0.223		
	531	0.257		
	559	0.288		
	585	0.317		
	617	0.354		
	643	0.388		
	673	0.419		
	698	0.452		
	730	0.490		
	753	0.519		
	782	0.550		
	810	0.583		
	829	0.601		

*Not shown in figure.

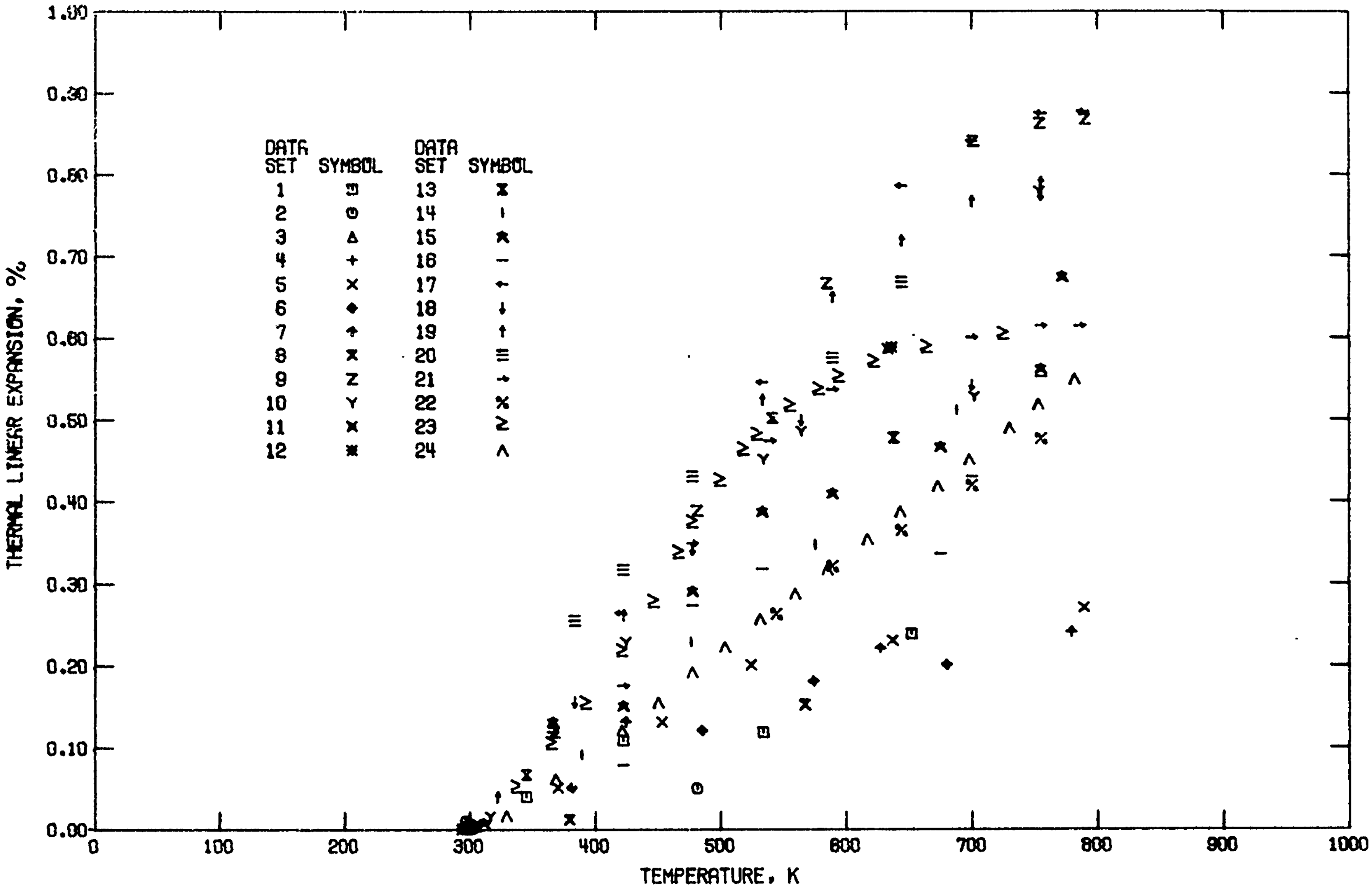

FIGURE 13. THERMAL LINEAR EXPANSION OF E GLASS FIBER. ALUMINUM-2014 MATRIX COMPOSITE.

1.9. BORON FILAMENT, ALUMINUM-2024 MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Gerdeman et al. [1] reported data for a composite containing 40 volume percent boron filaments in an Al-2024 matrix. The specimens in addition to being hot pressed at high pressure, solution treated and water quenched were aged 50 hours at 340°F. Measurements on the several specimens yielded fairly consistent results.

REFERENCE

1. Gerdeman, D.A., Wurst, J.C., Cherry, J.A., and Berner, W.E., U.S. Air Force Rept. AFML-TR-6853, 94 pp., 1968. [AD-835 768]

TABLE 10. DATA ON THE THERMAL LINEAR EXPANSION OF BORON FILAMENT, ALUMINUM-2024 MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	300	0.007	Composites consisted of 0.004 - 0.005 inch diameter and 40 volume % boron filaments in Al 2024 matrix; total thickness of composite 0.045 inch; plasma sprayed, hot pressed 3 hours at 20 ksi and 750°F, solution heat treated 10 min. at 930°F, water quenched and aged 50 hours at 340°F; quartz dilatometer; measurements on several samples during both heating and cooling cycles which was repeated at least twice; Leitz dilatometer; results of run No. 1; measurement direction not reported; data extracted from figure; zero point correction is -0.004%.	Gerdeman, D. A., Wurst, J. C., Cherry, J. A., and Berner, W. E.,
	309	0.026 *		
	365	0.127		
	420	0.226 *		
	475	0.329		
	532	0.435		
	587	0.549		
2 [1]	300	0.009	Similar to the above except results of run No. 2; zero po. t correction of -0.002%.	Gerdeman, D. A., et al., 1968
	310	0.028		
	365	0.127 *		
	419	0.231		
	475	0.340		
	532	0.448		
	587	0.563		

*Not shown in figure.

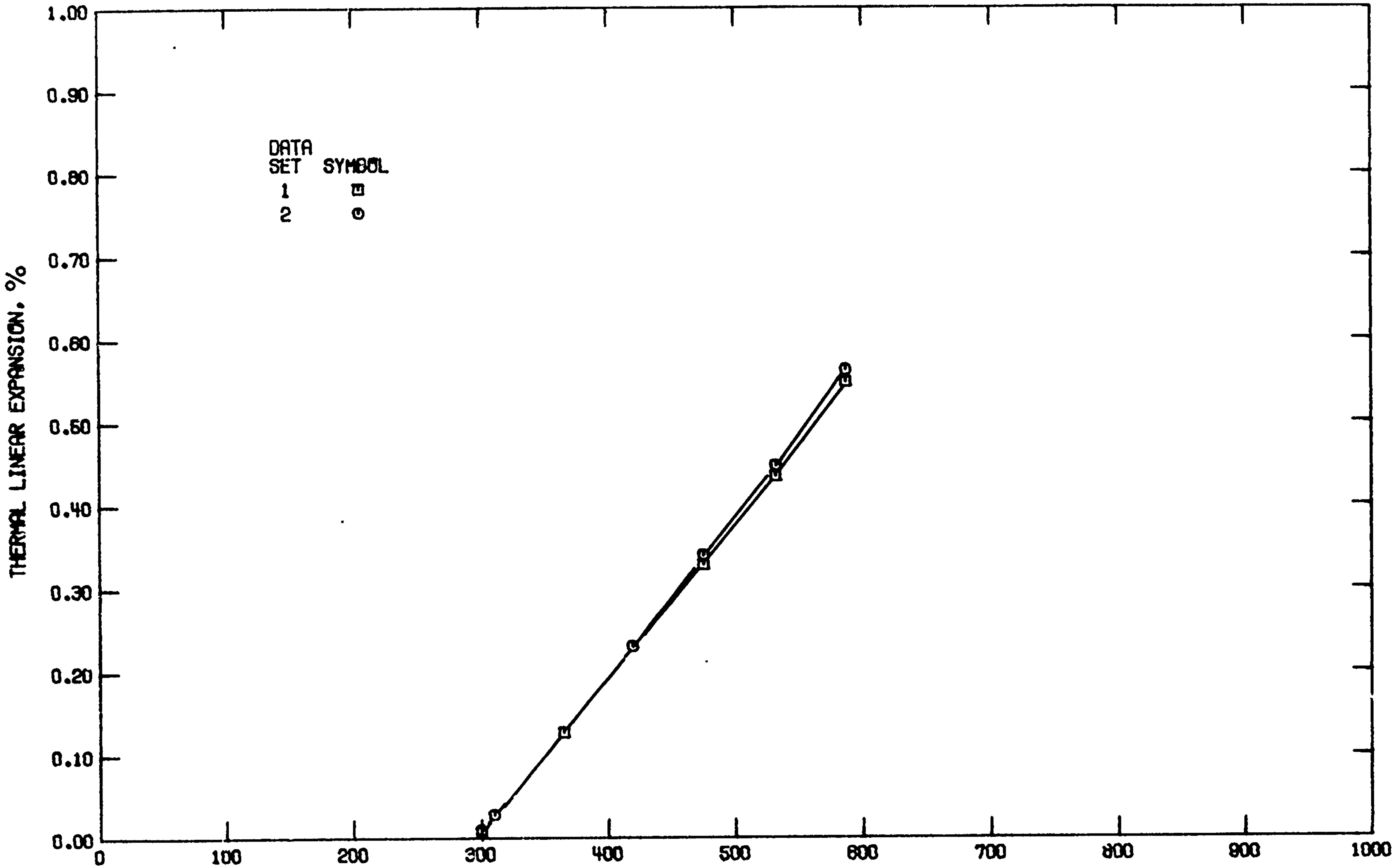

FIGURE 14. THERMAL LINEAR EXPANSION OF BORON FILAMENT. ALUMINUM-2024 MATRIX COMPOSITE.

1.10. BORSIC FIBER, ALUMINUM-2024 MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Kreider and Patarini [1] reported thermal expansion data for hot pressed and diffusion bonded composites containing 55 volume percent Borsic fibers. These data included results of measurements for seven composites which were cut from 0 deg. to 90 deg. relative to the fiber axis. Percent thermal expansion near 570 K increased from 0.116 for a 0 deg. cut to 0.573 for a 90 deg. cut in a fairly regular manner.

REFERENCE

1. Kreider, K.G. and Patarini, V.M., Trans. Met. Soc. AIME, 1(12), 3431-5, 1970.

TABLE 11. DATA ON THE THERMAL LINEAR EXPANSION OF BORSIC FIBER, ALUMINUM-2024 MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	296	0.004	Composites were hot-pressed diffusion bonded at 20 - 40° C below their matrix solidus temperature and 5000 psi from plasma sprayed monolayer tapes; slow cool was used to minimize residual stresses and yielded an "annealed" structure; measurements with quartz tube dilatometer; 55 volume % fiber content; test specimen cut 0 deg. to the fiber axis (longitudinal); data extracted from figure.	Kreider, K. G., and Patarini, V. M., 1970
	323	0.011 *		
	374	0.039		
	424	0.068		
	475	0.102		
	524	0.134		
	574	0.166		
2 [1]	296	0.002	Similar to the above except specimen cut 75 deg. to the fiber axis.	Kreider, K. G., and Patarini, V. M., 1970
	322	0.036		
	374	0.115 *		
	422	0.208		
	473	0.310		
	522	0.414		
	571	0.532		
3 [1]	296	0.002	Similar to the above except specimen cut 90 deg. to the fiber axis (transverse).	Kreider, K. G., and Patarini, V. M., 1970
	322	0.050		
	373	0.142		
	422	0.239		
	472	0.341		
	521	0.451		
	571	0.573		

TABLE 11. DATA ON THE THERMAL LINEAR EXPANSION OF BORSIC FIBER, ALUMINUM-2024 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
4 [1]	297	0.002	Similar to the above except specimen cut 60 deg. to the fiber axis.	Kreider, K. G., and Patarini, V. M., 1970
	324	0.032		
	374	0.099		
	422	0.177		
	474	0.261		
	522	0.356		
	571	0.451		
5 [1]	296	0.002	Similar to the above except specimen cut 45 deg. to the fiber axis.	Kreider, K. G., and Patarini, V. M., 1970
	323	0.028		
	373	0.092		
	403	0.118		
	423	0.147		
	474	0.217		
	521	0.282		
	546	0.326		
	572	0.361		
6 [1]	296	0.004	Similar to the above except specimen cut 30 deg. to the fiber axis.	Kreider, K. G., and Patarini, V. M., 1970
	323	0.024		
	374	0.076		
	423	0.126		
	474	0.180		
	523	0.227		
	572	0.287		
7 [1]	296	0.004	Similar to the above except specimen cut 15 deg. to the fiber axis.	Kreider, K. G., and Patarini, V. M., 1970
	323	0.015		
	374	0.045		

TABLE 11. DATA ON THE THERMAL LINEAR EXPANSION OF BORSIC FIBER, ALUMINUM-2024 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	<u>THERMAL LINEAR EXPANSION</u> (cont.)	
7 (cont) [1]	423	0.077		
	475	0.113		
	523	0.146		
	574	0.184		

*Not shown in figure.

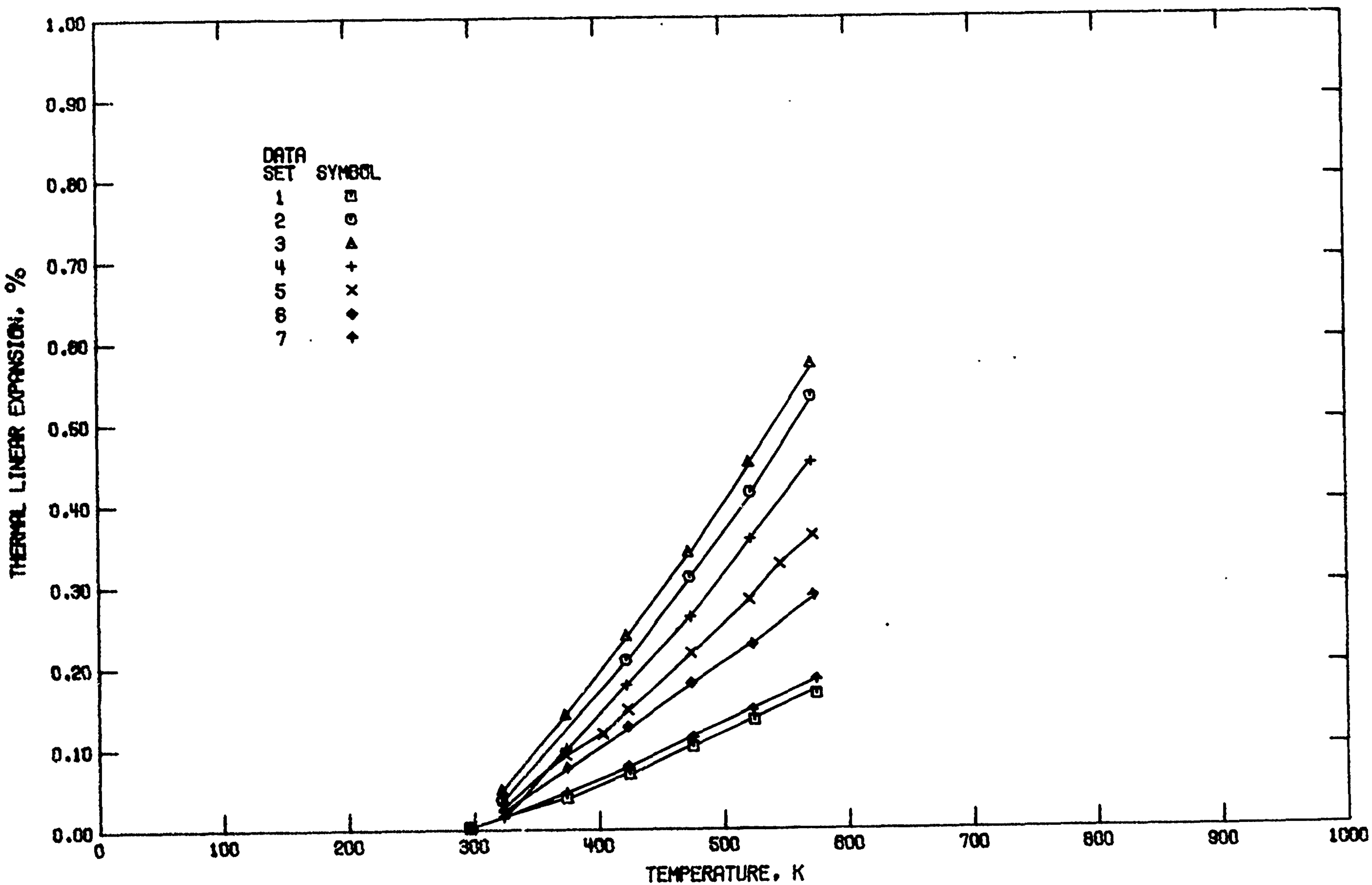

FIGURE 15. THERMAL LINEAR EXPANSION OF BORSIC FIBER, ALUMINUM-2024 MATRIX COMPOSITE.

1.11. AM 355 STAINLESS STEEL WIRE, ALUMINUM-2024-T81 MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Gerdeman et al. [1] reported the thermal expansion for a composite containing 25 volume percent steel wires. The measurements were on a specimen which had undergone various heat treatments such as hot pressing, cold working, and ageing. During the first heating, the specimen began to contract above 500°F and about 0.3% permanent and irreversible contraction was observed. Subsequent tests yielded fairly reproducible results.

REFERENCE

1. Gerdeman, D.A., Wurst, J.C., Cherry, J.A., and Berner, W.E., U.S. Air Force Rept. AFML-TR-6853, 94 pp., 1968. [AD-835 768]

TABLE 12. DATA ON THE THERMAL LINEAR EXPANSION OF AM 355 STAINLESS STEEL WIRE, ALUMINUM-2024-T81 MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	309 366 421 478 533 539	0.084 0.182 0.283 0.388 0.495 0.605	Composite consisted of 0.009 inch diameter and 25 volume % AM 355 stainless steel wires in Al 2024-T81 matrix; total thickness 0.250 inch hot pressed at 900°F for 30 min., solution treated for one hour at 910°F; 2% cold worked and aged for 10 hours at 375°F and finally 1% cold worked; quartz dilatometer; average of two heating experiments; during the first heating the specimen above 500°F began to contract; approximately 0.3% permanent and irreversible contraction was observed; in subsequent tests fairly good reproducible results were obtained; permanent contraction near 400°F is both time and temperature dependent; the results are for first cooling experiment; data extracted from figure; measurement direction not reported; zero point correction is 0.360%.	Gerdeman, D. H., Wurst, J. C., Cherry, J. A., and Berner, W. E., 1968
2 [1]	305 311 366	0.018 0.026 0.108	Similar to the above except second heating experiment; zero point correction is 0.290%.	Gerdeman, D. H., et al., 1968

TABLE 12. DATA ON THE THERMAL LINEAR EXPANSION OF AM 355 STAINLESS STEEL WIRE, ALUMINUM-2024-T81 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_c$	THERMAL LINEAR EXPANSION (cont.)	
2 (cont.) [1]	422	0.200		
	478	0.304		
	534	0.408		
	589	0.500		
3 [1]	293	0.000	Similar to the above except second cooling experiment; zero point is 0.286%.	Gerdeman, D. H., 1968
	311	0.030		
	366	0.125		
	422	0.219		
	463	0.281		
	517	0.385		
	534	0.418		
	589	0.511		

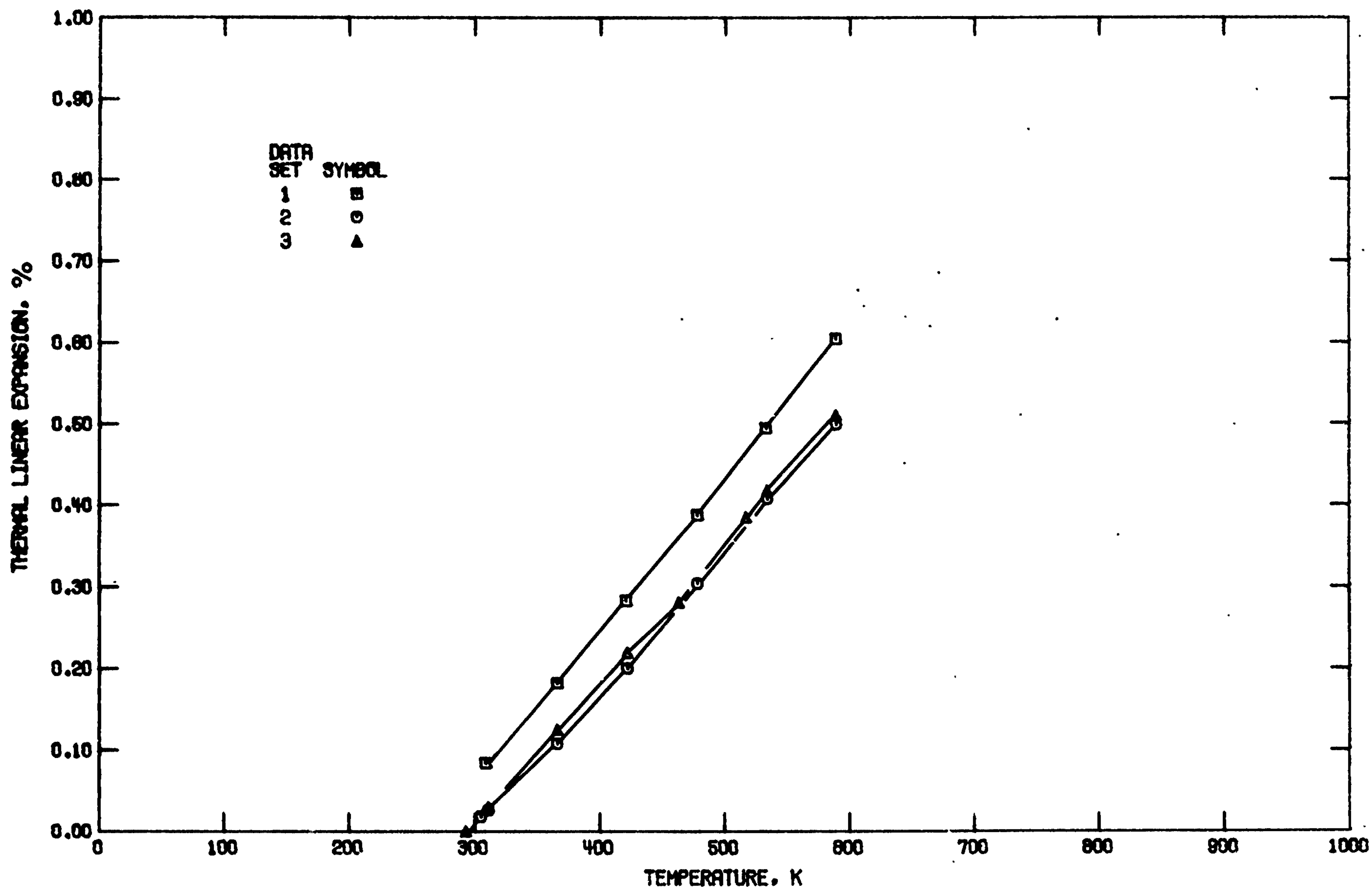

FIGURE 16. THERMAL LINEAR EXPANSION OF AM 355 STEEL STAINLESS STEEL WIRE, ALUMINUM-2024T81 MATRIX COMPOSITE.

1.12. BORON FIBER, ALUMINUM-6061 MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Christian and Campbell [1], Hertz et al. [2], Hofer et al. [3], Schramm and Kasen [4], Wolff and Eselun [5], and Cairo and Torczyner [6] reported thermal expansion data for various types of composites containing unidirectional laid-up 47 to 55 volume percent boron fibers in an aluminum-6061 alloy matrix. The measurements in axial and transverse directions yielded fairly consistent results for the most part.

THERMAL CONDUCTIVITY

There are three references [3,7,8] in which the thermal conductivity of boron fiber Al-6061 matrix composite is reported: ref. [3] for the temperature range ~70 - 670 K, ref. [7] 7 - 276 K, and ref. [8] 122 - 406 K. The first two references contain data for specimens having fiber contents of ~50%, and for heat flow in the parallel and the perpendicular (to the fiber) directions. Ref. [8] reported data on boron fiber Al-6061-0 matrix composite. The data included one set for an 8-ply panel, with 2 parallel outer plys and four perpendicular center-cross plys. This data set was for heat flow parallel to the outer plys. Two other data sets, one for heat flow parallel to and one for heat flow perpendicular to the plys, were for 7-ply panels. These panels were made by diffusion press bonding, with silicon/aluminum sheet placed between the plys and at the outer surfaces.

SPECIFIC HEAT

Christian and Campbell [1] and Hertz et al. [2] reported specific heat data for unidirectionally laid up 44.1 volume percent 0.14 mm diameter boron fibers in an aluminum alloy 6061 matrix. Their value of 985 J kg^{-1} K^{-1} at 297 K was compatible with the value of 970 J kg^{-1} K^{-1} at 300 K reported by Collings and Smith [9] .

REFERENCES

1. Christian, J.L. and Campbell, M.D., Proc. Cryogen. Eng. Conf., 175-83, 1973.
2. Hertz, J., Christian, M.D., Varlas, M., et al., U.S. Air Force Rept. AFML-TR-71, Vol. 2, 394 pp., 1972. [AD-893 715]
3. Hofer, K.E., Rao, N., and Larsen, D., U.S. Air Force Rept. AFML-TR-72-205-Pt-2, 470 pp., 1974. [AD015 907]
4. Schramm, R.E. and Kasen, M.B., Materials Sci. Eng., 30(3), 197-204, 1977. [PB 278 418]
5. Wolff, E.G. and Eselun, S.A., J. Compos. Mater., 11(1), 130-2 , 1976.
6. Cairo, R.P. and Torczyner, R.D., U.S. Air Force Rept. AFML-TR-72-232, 115 pp., 1972. [AD-908 249L]
7. Hust, J.G., Natl. Bur. Stand. Rept. NBSRI-76-848, 305-19, 1976. [PB 261 996]
8. O'Kelly, K.P., NASA Rept. NASA-CR-115221, 79 pp., 1971. [N72-11432]
9. Collings, E.W. and Smith, R.D., Adv. Cryog. Eng., 24, 290-6, 1978.

TABLE 13. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORON FIBER, ALUMINUM-6061 MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %; Thermal Conductivity, λ, W m^{-1} K^{-1}; Specific Heat, c_p, J Kg^{-1} K^{-1}]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	77	-0.289	Boron/Aluminum matrix, boron 0.14 mm diameter, 44.1 volume %; 6061 aluminum sheet 55.9 volume %; unidirectional layup, diffusion bonding; sheet thickness 1.07 mm; density 2.60 g/cc; measurements in transverse direction; quartz tube dilatometer; values calculated from tabular values of the mean coefficient of thermal expansion and additional information obtained from authors.	Christian, J. L., and Campbell, M. D., 1973
	144	-0.229		
	297	0.006		
	450	0.282		
	644	0.745		
2 [1]	77	-0.071	Boron/Aluminum matrix, boron 0.14 mm diameter, 44.1 volume %; 6061 aluminum sheet 55.9 volume %; unidirectional layup, diffusion bonding; sheet thickness 1.07 mm; density 2.60 g/cc; measurements in longitudinal direction; values calculated from tabular values of the mean coefficient of thermal expansion and information obtained from authors.	Christian, J. L., Campbell, M. D., 1973
	144	-0.056		
	297	0.002 *		
	450	0.094		
	644	0.211		

TABLE 13. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORON FIBER, ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp. T	Prop. $\Delta L/L_0$	Specifications and Remarks	Author(s), Year
			THERMAL LINEAR EXPANSION (cont.)	
3 [2]	78	-0.143	5.6 mil (large diameter) boron/aluminum tape panels; monolayer sheets in size of 12 x 4 inch and 4 x 4 inch (both six ply thick); consolidation cycle consisted of one hour soak at 900°F and 3000 psi, and 30 minutes soak at 975°F and 3000 psi; tape panels contain 44.1 volume % boron; measurements on unidirectional composite in 0° direction (longitudinal); dilatometry, data extracted from figure.	Hertz, J., Christian, J. L., and Varlas, M., et al., 1972
	102	-0.141 *		
	158	-0.104		
	211	-0.060 *		
	268	-0.022		
	293	0.000		
	352	0.035 *		
	379	0.055		
	409	0.070		
	435	0.085		
	465	0.098 *		
	492	0.113		
	521	0.129 *		
	547	0.146		
	574	0.164		
	603	0.183 *		
	630	0.203		
	643	0.213 *		
4 [2]	79	-0.730 *	Similar to the above except measurements on undirectional composite in the 90° direction (transverse), data extracted from figure.	Hertz, J., et al., 1972
	105	-0.691 *		
	132	-0.538 *		
	185	-0.439 *		
	242	-0.225		
	270	-0.126		
	293	0.000		
	350	0.083		
	381	0.141		
	411	0.198		

TABLE 13. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORON FIBER, ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
4 (cont.) [2]	436	0.255		
	465	0.315 *		
	492	0.375		
	521	0.450		
	547	0.504 *		
	577	0.570		
	605	0.654		
	638	0.747		
5 [3]	103	-0.062 *	Composite obtained from Amercom incorporated who fabricated the material in laminate form; it was diffusion bonded; initially assembled by winding boron filaments onto a thin foil of aluminum-6061; filaments were held in place by a "fugitive binder", the sheets of foil and filaments were then assembled to the requisite lamination, placed in a stainless steel vacuum bag and the bag was evacuated; the binder was eliminated at a low pressure and temperature under dynamic pressure; consolidation was carried out in the solid state under pressure at high temperature; then chemically cleaned; approximately 50 volume % boron fiber; average of five samples in the 0° fiber orientation; heating	Hofer, K. E., Jr., Rao, N., and Larsen, D., 1974
	144	-0.054		
	199	-0.037 *		
	255	-0.017		
	312	0.010 *		
	367	0.042		
	423	0.075		
	478	0.106 *		
	533	0.133		
	589	0.158 *		
	644	0.186		

TABLE 13. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORON FIBER, ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
5 (cont.) [3]			cycle; data on the coefficient of thermal expansion also reported; zero point correction is -0.082%, data extracted from figure.	
6 [3]	104	-0.058	Similar to the above except measurements in the 0° fiber orientation; cooling cycle; zero point correction is -0.074%.	Hofer, K. E., Jr., et al., 1974
	144	-0.051 *		
	201	-0.035 *		
	256	-0.015 *		
	311	0.008		
	368	0.028 *		
	423	0.054		
	478	0.081		
	534	0.144		
	588	0.153		
	641	0.188 *		
7 [3]	104	-0.265	Similar to the above except heating cycle in the 90° fiber orientation.	Hofer, K. E., Jr., et al., 1974
	142	-0.222 *		
	200	-0.149		
	256	-0.064 *		
	311	0.024		
	368	0.124 *		
	423	0.232		
	478	0.344		
	532	0.458		
	587	0.576		
	642	0.696		

TABLE 13. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORON FIBER, ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
8 [3]	105	-0.255	Similar to the above except cooling cycle in the 90° fiber orientation.	Hofer, K. E., Jr., et al., 1974
	145	-0.202		
	202	-0.124		
	257	-0.053 *		
	313	0.004 *		
	367	0.144		
	423	0.251		
	478	0.367		
	533	0.477 *		
	588	0.587 *		
	642	0.694		
9 [4]	80	-0.084	5.6 mil uniaxial boron fiber; fiber volume % 47.2; expansion in longitudinal (fiber) direction; data of Jelinek, F. of Battelle Columbus Laboratory; zero point correction is -0.006%, data extracted from figure.	Schramm, R. E. and Kasen, M. B., 1977
	100	-0.076		
	200	-0.038		
	300	0.004		
10 [4]	82	-0.244	Similar to the above except thermal expansion in transverse direction; zero point correction is -0.001%.	Schramm, R. E. and Kasen, M. B., 1977
	101	-0.225 *		
	153	-0.184		
	198	-0.136 *		
	252	-0.060		
	274	-0.017		
	289	-0.001 *		
	299	0.007 *		

TABLE 13. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORON FIBER, ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
11 [5]	290	-0.002	Axially reinforced tube, 10.94 cm. long and 5.66 cm. O.D. with a 0.10 cm. wall thickness fabricated by an isostatic hot pressing technique; 50 volume % of untreated 0.014 cm. diameter; boron fibers in aluminum 6061 matrix; the final treatment was slow cooling from 525°C; data points taken at random intervals from five thermal cycles; axial (0 degree) expansion; zero point correction is +0.002%, data extracted from figure.	Wolff, E. G. and Eselun, S. A., 1976
	303	0.007 *		
	323	0.026		
	353	0.053		
	375	0.070		
	381	0.076		
12 [5]	293	0.000 *	Similar to the above except transverse (90 degree) expansion (i.e., diametric).	Wolff, E. G. and Eselun, S. A., 1976
	303	0.011 *		
	323	0.040 *		
	341	0.069 *		
	354	0.088 *		
	374	0.122 *		
	393	0.156 *		
	398	0.168 *		
13 [6]	293	0.000	Each ply consisted of 5.6 mil boron fiber diffusion bonded to two layers of aluminum-6061F foil 2 and 1.3 mils thick; packing 135 filaments per inch yields a filament volume 47.5 % with thickness of 7.0 mils; laminate plies	Cairo, R. P. and Torczyner, R. D., 1972
	450	0.050		

TABLE 13. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORON FIBER, ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
13 (cont.) [6]			stacked and diffusion bonded by Armco Incorporated; density 0.095 lb. In^{-3}; longitudinal measurements, values calculated from tabulated values of instantaneous coefficient of thermal expansion.	
14 [6]	293	0.000	Similar to the above specimen except transverse direction.	Cairo, R. P. and Torczyner, R. D., 1972
	450	0.166		
	T	λ	THERMAL CONDUCTIVITY	
1 [3]	69	65.8	Supplied by Americom Inc., in laminate form; prepared by vacuum diffusion bonding; boron filaments of 5.6 mil were first wound onto Al-6061 foil and held by a "fugitive binder"; foil and filaments were then assembled to the requisite lamination, placed in a stainless steel bag and evacuated; binder eliminated at low pressure and temperature under a dynamic vacuum; consolidated at high temperature under pressure; trimmed and chemical cleaned; fiber volume content ~50%; measured with heat flow parallel to fiber direction; smoothed values from graph.	Hofer, K. E., Rao, N., and Larsen, D., 1974
	147	71.2		
	202	75.1		
	258	79.2		
	313	83.1		
	369	87.0		
	424	91.1		
	481	95.0		
	537	99.1		
	591	102.8		
	645	106.6		
	671	108.6		

TABLE 13. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORON FIBER, ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
2 [3]	73	59.3	The above with heat flow perpendicular to fiber direction.	Hofer, K. E., et al., 1974
	147	60.5		
	203	61.4		
	258	62.4		
	312	63.3		
	368	64.3		
	424	64.8		
	480	66.0		
	536	67.0		
	590	67.7		
	644	68.7		
	670	69.1		
3 [7]	7	17.7	Ofabricated with 5.6 mil boron fibers and 6061-F aluminum; aluminum content 53%, void content <2%; measured by a "fixed point apparatus", capable of measuring near the fixed temperatures of various boiling liquids and melting or subliming solids with specimen epoxy-bonded to copper end pieces for thermal contact; measurement accuracy ~10%; heat flow longitudinal to fibers; values from table.	Hust, J. G., 1976
	78	75.1		
	195	82.2		
	276	89.6		
4 [7]	7	11.3	Similar to the above except heat flow transverse to fibers.	Hust, J. G., 1976
	78	51.3		
	195	55.7		
	276	60.6		

TABLE 13. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORON FIBER, ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
5 [8]	191 290 404	71.0 79.4 80.4	8 ply boron fiber, aluminum 6061-0 matrix panel, made of 2 panellel outer plys and four 90° center cross plys with 0.001 in silicon/aluminum foils placed between the plys and at the surfaces; the plys were monolayer tapes diffusion press bonded from 2 sheets of 0.002 in. thick aluminum 6061-0 foil having 0.004 in diameter boron filaments between foils; 0.001 in silicon/aluminum foils were placed between the plys and at the outer surface for the final assembly, which is also diffusion press bonded; boron fiber volume 45-50%; heat flow in a direction parallel to the outer plys.	O'Kelly, K. P., 1971
6 [8]	122 205 239 287 335 385 437	114.9 120.2 122.8 125.8 128.2 129.5 129.8	Similar to the above except 7 ply panel with all plys in parallel alignment boron fiber volume 30-35%; heat flow parallel to the plys.	O'Kelly, K. P., 1971
7 [8]	137 210 287 339 406	87.6 92.9 97.0 98.1 98.2	Similar to the above except heat flow perpendicular to the plys.	O'Kelly, K. P., 1971

TABLE 13. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORON FIBER, ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	c_p	SPECIFIC HEAT	
1 [1]	88 297 450 644	440. 985. 1230. 1470.	Boron/Aluminum matrix, Boron 0.14 mm diameter, 44.1 volume %; aluminum-6061 sheet 55.9 volume %; unidirectional layup, diffusion bonding; sheet thickness 1.07 mm; density 2.60 g cm^{-3}; below room temperature dynamic heating method and drop calorimeter above room temperature was used; data extracted from table.	Christian, J. L., and Campbell, M. D., 1973
2 [9]	2 4 5 10 15 20 80 300	0.057 0.139 0.196 0.759 2.050 4.590 207. 970.	Samples cut from 3 mm thick sheets 15-ply uniaxial fiber-reinforced 0.14 mm boron/aluminum-6061; 49.1 weight % aluminum.	Collings, E. W, and Smith, R. D., 1978
3 [2]	89 141 254 364 476 588 849	343. 569. 898. 1110. 1297. 1494. 1607.	5.6 mil. (large diameter) boron/aluminum-6061 tape panels; monolayer sheets in size of 12 x 4 inch and 4 x 4 inch (both six-ply thick); consolidation cycle consisted of one hour soak at 900°F and 3000 psi, and 30 minutes soak at 975°F and 3000 psi; tape panels contain 44.1 volume % boron; data extracted from figure.	Hertz, J., Christian, J. L., and Varlas, M., et al., 1972

*Not shown in figure.

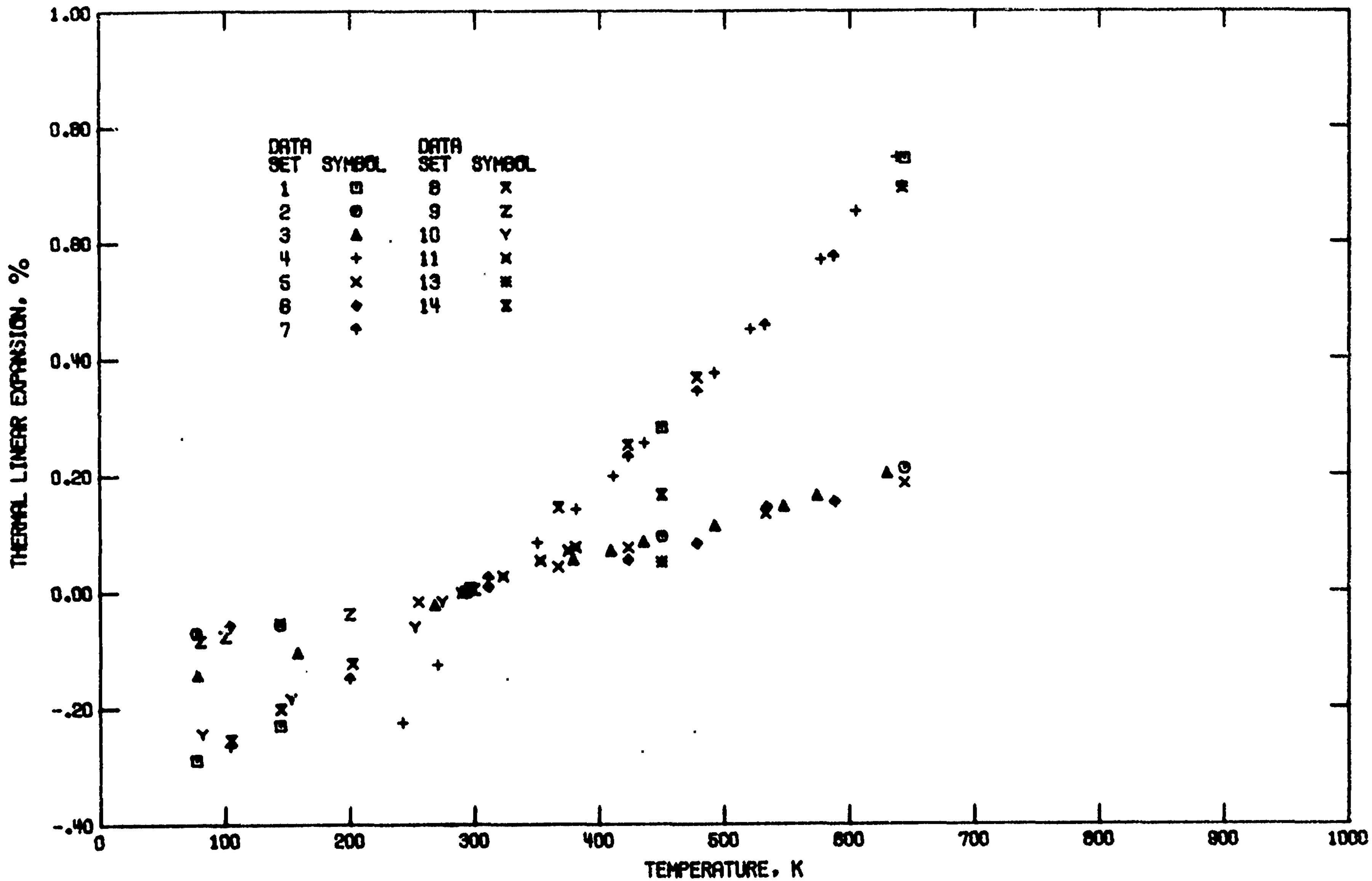

FIGURE 17. THERMAL LINEAR EXPANSION OF BORON FIBER, ALUMINUM-6061 MATRIX COMPOSITE.

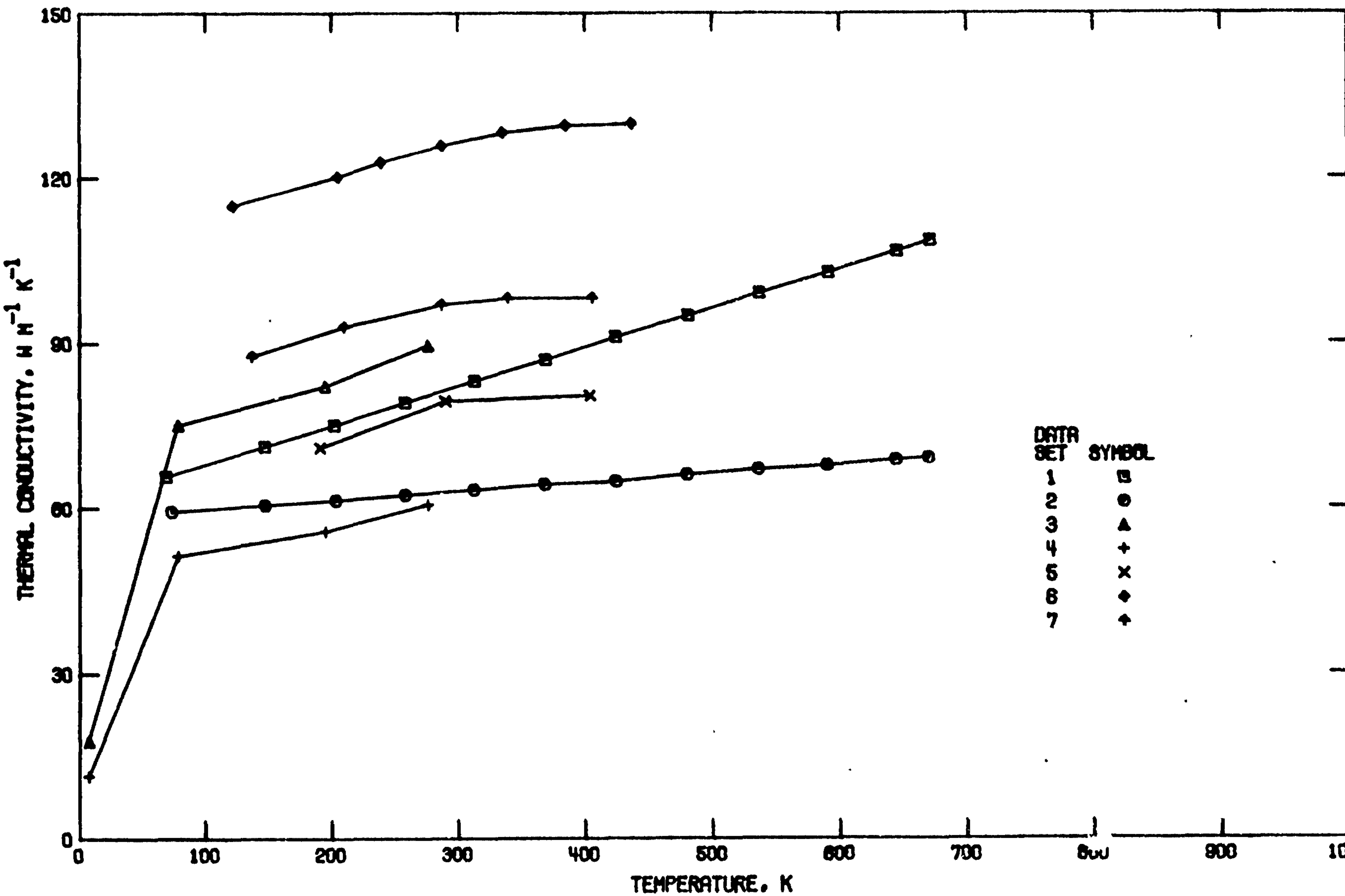

FIGURE 18. THERMAL CONDUCTIVITY OF BORON FIBER. ALUMINUM-6061 MATRIX COMPOSITE.

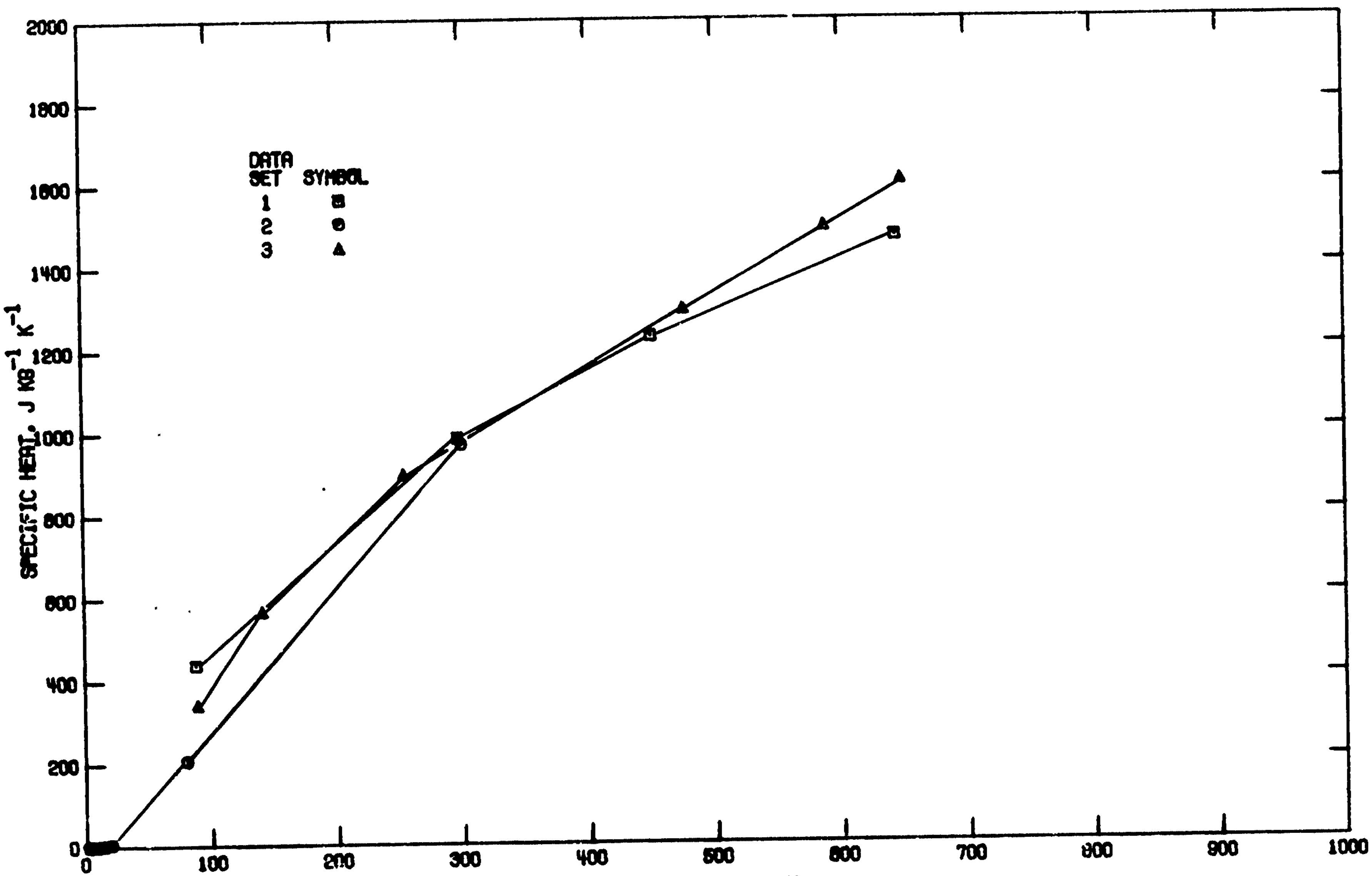

FIGURE 19. SPECIFIC HEAT OF BORON FIBER, ALUMINUM-6061 MATRIX COMPOSITE.

1.13. BORON FIBER/AM 350 STAINLESS STEEL WIRE, ALUMINUM-6061 MATRIX COMPOSITE

THERMAL CONDUCTIVITY

There is one reference [1] in which the thermal conductivity of boron fiber / stainless steel wire aluminum-6061-0 matrix composite is reported. The single specimen consisted of 3-3-3 ply panels, with the outer three plys made from boron filaments. The three plys at the center were made from AM 350 stainless steel wires. The alignment of the panels was such that the outer plys were parallel to each other, and the center three plys were at right angles to the outer ones. The panels and the final composite were made by diffusion press bonding. The thermal conductivity data reported were for heat flow in the plane of the panels and parallel to the direction of the outer plys.

REFERENCE

1. O'Kelly, K.P., NASA Rept. NASA-CR-115221, 79 pp., 1971. [N72-11432]

TABLE 14. DATA ON THE THERMAL CONDUCTIVITY OF BORON FIBER/AM 350 STAINLESS STEEL WIRE, ALUMINUM-6061 MATRIX COMPOSITE

[Temperature, T, K; Thermal Conductivity, λ, W m^{-1} K^{-1}]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY	
1 [1]	193	118.5	9 ply panel made from 3 parallel outer plys boron fiber, aluminum 6061-O tapes, and 3 center 90° cross plys stainless steel (AM 350) fiber, aluminum 6061-O tapes; the monolayer tapes are made from 0.004 inch diameter boron filament or 0.002 inch diameter rocket wires, diffusion press bonded to 2 sheets of 0.002 inch thick aluminum 6061-O foils; fiber content in boron/aluminum tape 30-35%, and in stainless steel/aluminum tape ~47%; the 9 ply assembly was also diffusion press bonded with 0.001 inch silicon/aluminum foils placed between the plys and at the outer surfaces; heat flow parallel to the outer plys.	O'Kelly, K. P., 1971
	245	123.2		
	296	127.7		
	345	130.7		
	398	132.4		
	450	133.7		
	495	134.3		

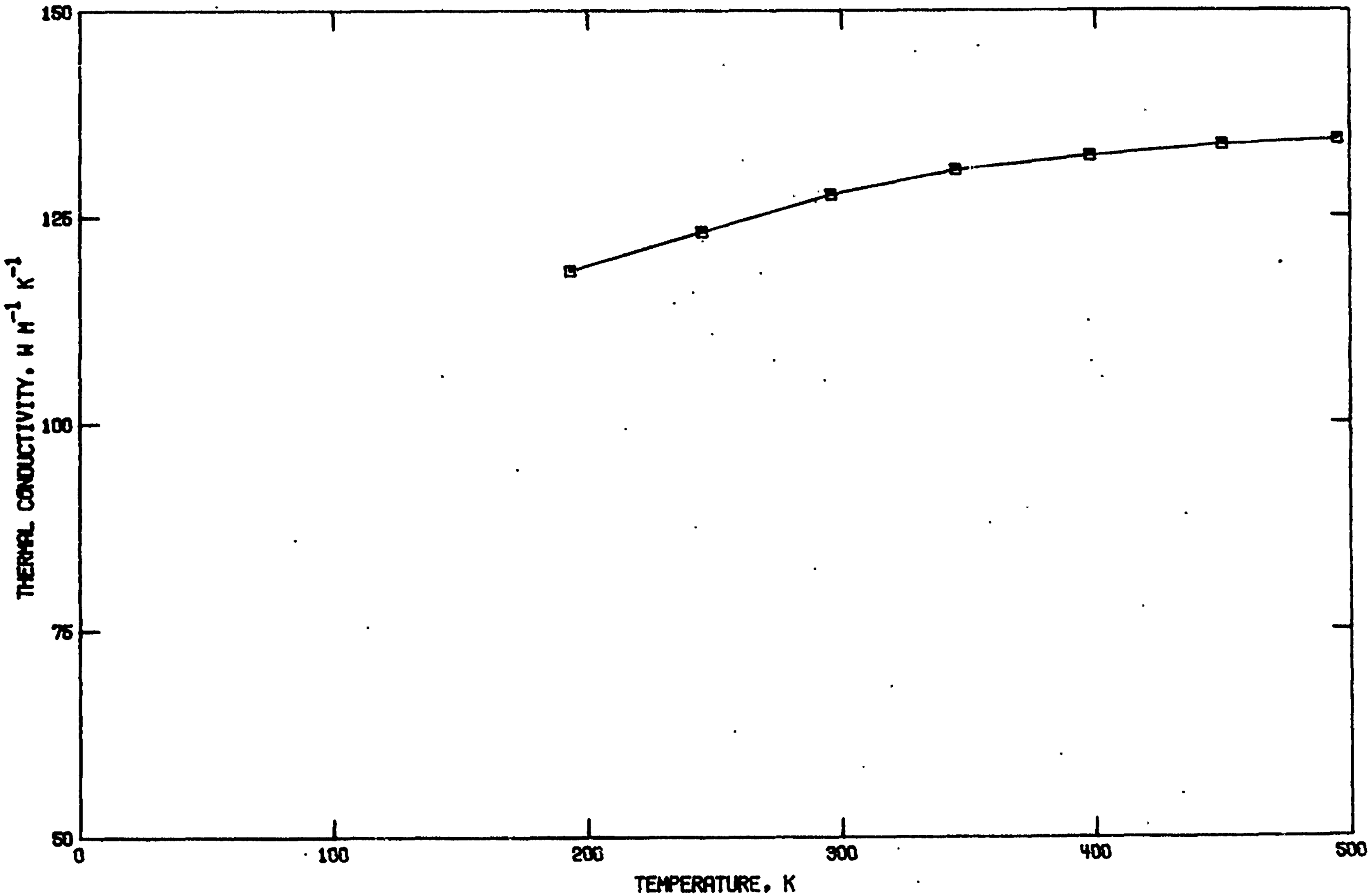

FIGURE 20. THERMAL CONDUCTIVITY OF BORON FIBER/AM 350 STAINLESS STEEL WIRE ALUMINUM-6061 MATRIX COMPOSIT.

1.14. BORSIC FIBER, ALUMINUM-6061 MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Christian and Campbell [1] and Hertz et al. [2] reported data for a composite containing 53 volume percent unidirectional Borsic fibers in an aluminum-6061 matrix. Thermal expansion along the fiber axis was fairly low (about 0.204% at 644 K); and perpendicular to fiber axis it was about 0.694% at 644 K. No attempt was made to resolve the discrepancy in the thermal expansion values below 293 K reported in these two references.

SPECIFIC HEAT

Hertz et al. [1] reported specific heat values of 406 to 1460 J kg K^{-1}at temperatures from 86 K to 642 K for a plasma-sprayed composite containing 47.2 volume percent Borsic filaments.

REFERENCES

1. Christian, J.L. and Campbell, M.D., Proc. Cryogen. Eng. Conf., 175-83, 1973.
2. Hertz, J., Christian, M.D., Varlas, M., et al., U.S. Air Force Rept. AFML-TR-71, Vol.2,, 394 pp., 1972. [AD-893 715]

TABLE 15. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FIBER, ALUMINUM-6061 MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %; Specific Heat, c_p, J Kg^{-1} K^{-1}]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	77 144 297 450 644	-0.282 -0.224 0.006 0.256 0.694	Borsic (trademark of the Hamilton Standard Division of United Aircraft Corporation for a silicon carbide coated boron filament)/aluminum matrix; borsic 0.1 mm diameter; 47.2 volume %; 6061 aluminum sheet 52.8 volume %; unidirectional layup; diffusion bonding of plasma sprayed tapes; sheet thickness 1.02 mm; density 2.66 gcm^{-3}; measurements along transverse direction; quartz tube dialtometer; values calculated from the reported tabular values of the mean coefficient and the additional information obtained from authors.	Christian, J. L. and Campbell, M. D., 1973
2 [1]	77 144 297 450 644	-0.085 -0.067 0.002 0.088 0.204	Similar to the above except measurements along longitudinal direction.	Christian, J. L. and Campbell, M. D.; 1973
3 [2]	76 100 131 158	-0.173 -0.164 -0.148 * -0.126 *	Plasma sprayed borsic/aluminum 6061 composite tape supplied by Union Carbide Corporation; 47.2 volume % borsic filament in the test panel;	Hertz, J., Christian, J. L., and Varlas, M., et al., 1972

TABLE 15. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FIBER, ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
3 (cont.) [2]	189	-0.100	borsic/6061 Al tapes were consolidated into panels at 900°F and 10000 psi for times ranging from one to three hours; convair bending rate 6.3; thermal expansion reported for unidirectional composite in 0° direction (longitudinal); dilatometry; data extracted from figure.	
	213	-0.075 *		
	244	-0.051		
	283	-0.020 *		
	302	0.002 *		
	331	0.018		
	359	0.035		
	415	0.067		
	470	0.096		
	527	0.128		
	555	0.140		
	582	0.157 *		
	632	0.189		
	650	0.202		
4 [2]	78	-0.679	Similar to the above except thermal expansion reported for unidirectional composite in the 90° direction (transverse).	Hertz, J., et al., 1972
	104	-0.642 *		
	130	-0.581		
	186	-0.427		
	215	-0.334		
	269	-0.122		
	300	0.002 *		
	353	0.062		
	381	0.116		
	409	0.165		
	437	0.219		
	463	0.274		
	491	0.346		
	518	0.403		

TABLE 15. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FIBER, ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s). Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
4 (cont.) [2]	546	0.467		
	606	0.597		
	632	0.657		
	645	0.693		
	T	c_p	SPECIFIC HEAT	
1 [2]	86	406.	Plasma sprayed Borsic/aluminum-6061 composite tape supplied by Union Carbide Corporation; 47.2 volume % Borsic filament in the test panel; Borsic/Al-6061 tapes were consolidated into panels at 900 F and 10000 psi for times ranging from one to three hours; convair bending rate 6.3; data extracted from figure.	Hertz, J., et al., 1972
	143	582.		
	201	741.		
	254	891.		
	311	1017.		
	364	1121.		
	425	1209.		
	476	1251.		
	539	1314.		
	585	1372.		
	642	1460.		

*Not shown in figure.

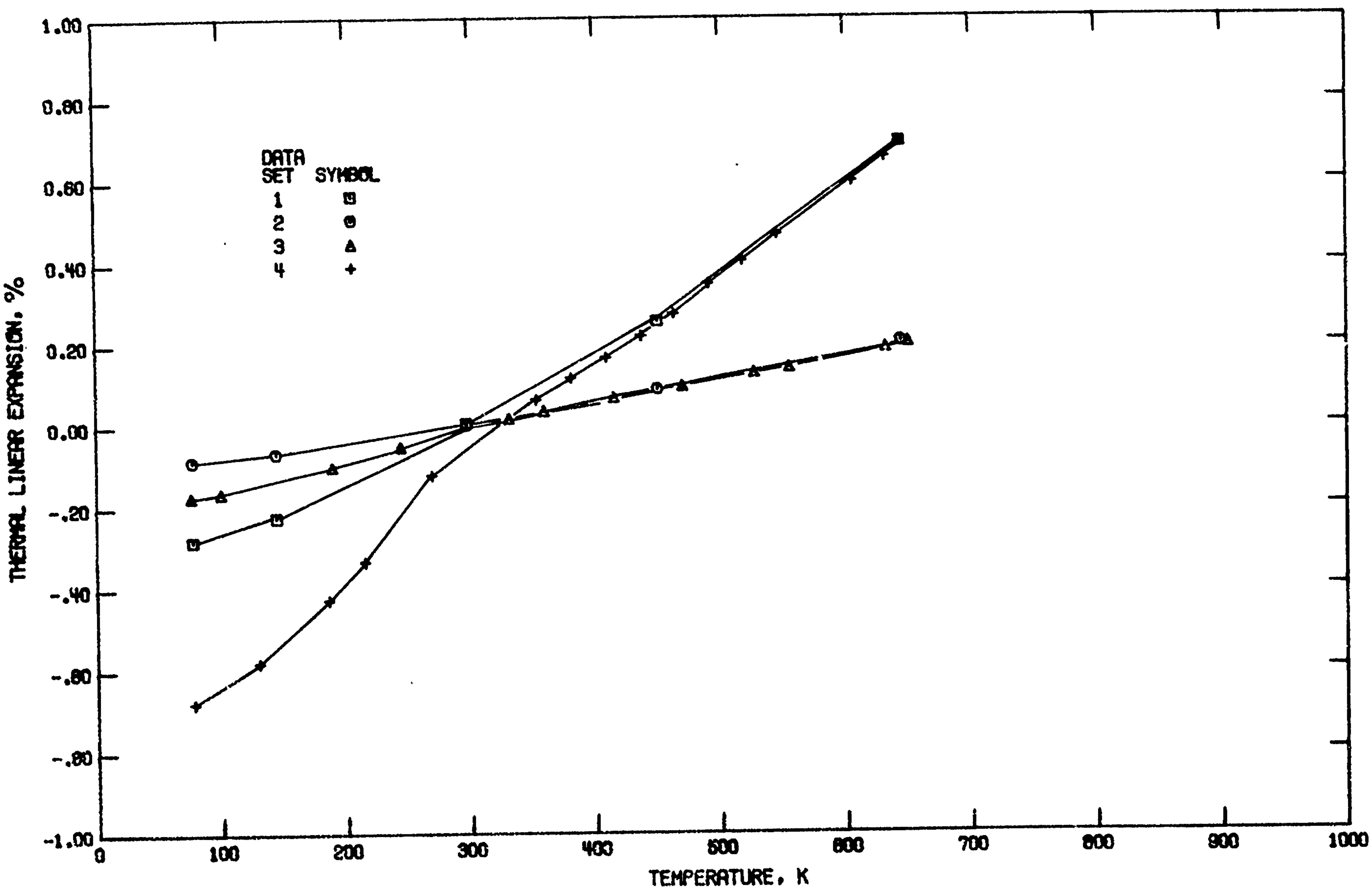

FIGURE 21. THERMAL LINEAR EXPANSION OF BORSIC FIBER, ALUMINUM-6061 MATRIX COMPOSITE.

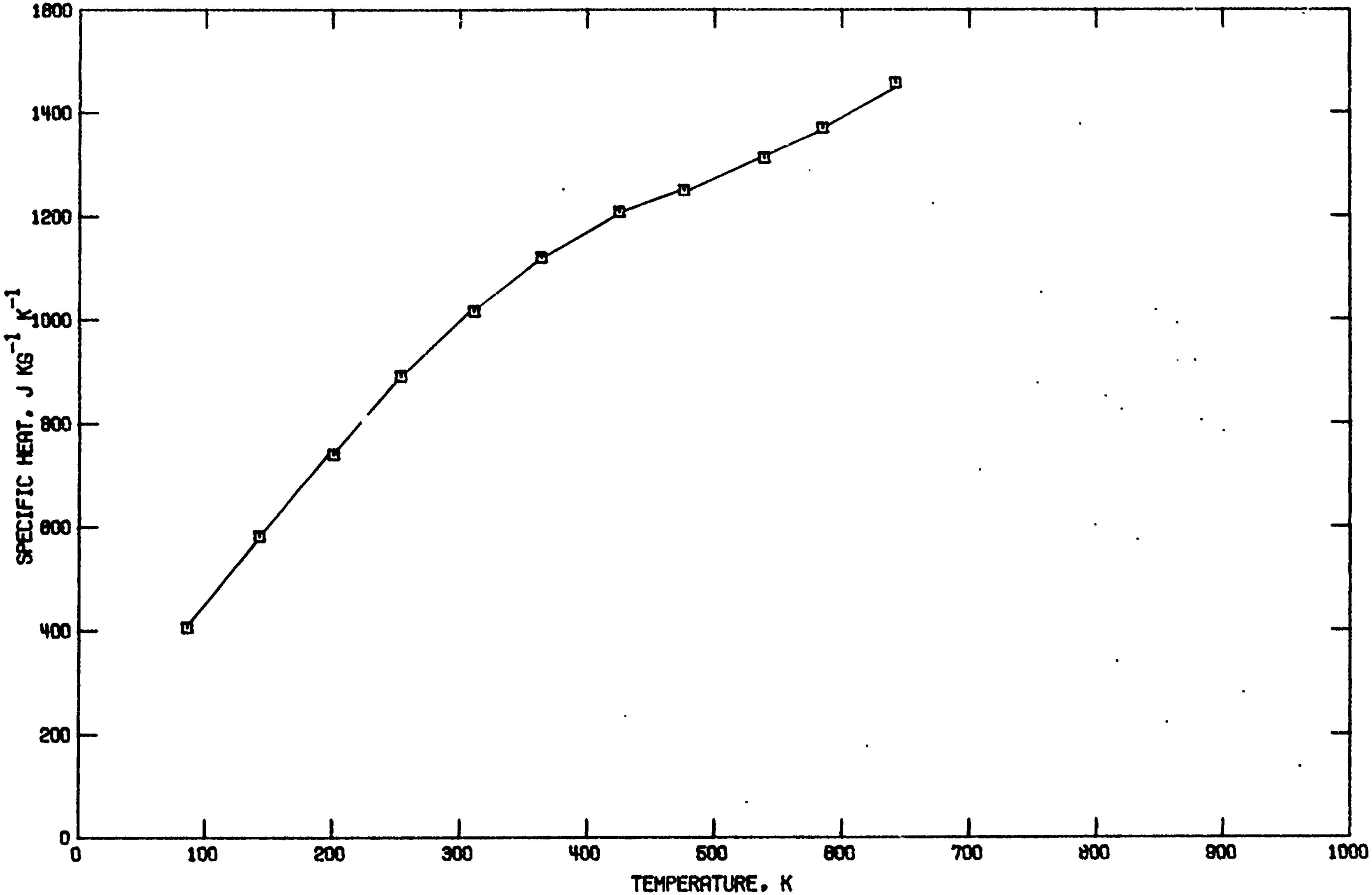

FIGURE 22. SPECIFIC HEAT OF BORSIC FIBER. ALUMINUM-6061 MATRIX COMPOSITE.

1.15. BORSIC FIBER, TITANIUM/ALUMINUM-6061 MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Christian and Campbell [1] and Hertz et al. [2] reported thermal expansion data for plasma-sprayed Borsic/Titanium/Aluminum tapes manufactured by United Aircraft Research Laboratory containing 49.1 volume percent Borsic filaments, 23.6 volume percent titanium, and 27.3 volume percent aluminum-6061 alloy. No attempt is made to reconcile the differences in thermal expansion below 293 K reported by these two investigators.

SPECIFIC HEAT

Christian and Campbell [1] and Hertz et al. [2] reported specific heat data for a 49.1 volume percent Borsic filament, 23.6 volume percent β-3 titanium foil, and 27.3 volume percent aluminum-6061 sheet composite made by diffusion bonding of plasma-sprayed tapes. Specific heat values range from 280 J kg^{-1} K^{-1} at 96 K to 1355 J kg^{-1} K^{-1} at 637 K [2].

REFERENCES

1. Christian, J.L. and Campbell, M.D., Proc. Cryogen. Eng. Conf., 175-83, 1973.
2. Hertz, J., Christian, M.D., Varlas, M., et al., U.S. Air Force Rept. AFML-TR-71, Vol. 2, 394 pp., 1972. [AD-893 715]

TABLE 16. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FIBER, TITANIUM/ALUMINUM-6061 MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %; Specific Heat, c_p, J Kg^{-1} K^{-1}]

Data Set [Ref.]	Temp. T	Prop. $\Delta L/L_0$	Specifications and Remarks	Author(s), Year
			THERMAL LINEAR EXPANSION	
1 [1]	77 144 297 450 644	-0.072 -0.056 0.002 0.086 0.225	Borsic (trademark of the Hamilton Standard Division of United Aircraft Corporation for a silicon carbide coated boron filament)/titanium/aluminum matrix, borsic 0.1 mm diameter, 49.1 volume %; β-3 titanium 0.025 mm foil, 23.6 volume %; 6061 aluminum sheet 27.3 volume %, unidirectional layup, diffusion bonding of plasma sprayed tapes, sheet thickness 1.02 mm, density 3.12 g/cc; measurements in longitudinal direction; quartz tube dilatometer; values are calculated from graphically reported mean coefficient of thermal expansion and additional information obtained from authors.	Christian, J. L. and Campbell, M. D. 1973
2 [1]	77 144 297 450 644	-0.191 -0.156 0.004 0.200 0.464	Borsic (trademark of the Hamilton Standard Division of United Aircraft Corporation for a silicon carbide coated boron filament)/titanium/aluminum matrix, borsic 0.1 mm diameter, 49.1 volume %; β-3 titanium 0.025 mm foil, 23.6 volume %; 6061 aluminum sheet 27.3	Christian, J. L. and Campbell, M. D. 1973

TABLE 16. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FIBER, TITANIUM/ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
2 (cont.) [1]			volume %, unidirectional layup, diffusion bonding of plasma sprayed tapes, sheet thickness 1.02 mm, density 3.12 g/cc; measurements in transverse direction; quartz tube dilatometer.	
3 [2]	73	-0.144	Plasma sprayed Borsic/Ti/Al tapes manufactured by United Aircraft Research Laboratory and purchased from Hamilton Standard; volume %age determined by leaching method indicates the tape contains 49.1 volume % Borsic filaments 23.6 volume % titanium and 27.3 volume % aluminum; tapes were consolidated into panels at 900F and 10000 psi for times ranging from one to three hours; thermal expansion reported for composite in 0° direction (longitudinal); dilatometry; data extracted from figure.	Hertz, J., Christian, M. D., and Varlas, M., et al. 1972
	101	-0.136		
	129	-0.120		
	159	-0.105		
	184	-0.087		
	240	-0.044		
	296	0.001		
	324	0.015		
	378	0.045		
	407	0.060		
	437	0.078		
	464	0.093		
	519	0.130		
	548	0.152		
	574	0.172		
	602	0.192		
	630	0.214		
	645	0.226		
4 [2]	76	-0.515	Similar to the above except thermal expansion reported for unidirectional composite in 90° direction	Hertz, J., et al. 1972
	128	-0.434		
	158	-0.379		

TABLE 16. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FIBER, TITANIUM/ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
4 (cont.) [2]	186	-0.313	(transverse).	
	212	-0.250		
	241	-0.162		
	270	-0.087		
	297	0.001		
	325	0.031		
	351	0.064		
	383	0.100		
	409	0.130		
	464	0.209		
	520	0.287		
	545	0.326		
	604	0.402		
	632	0.441		
	650	0.465		
	T	c_p	SPECIFIC HEAT	
1 [2]	96	280.	Plasma sprayed Borsic/Titanium/Aluminum tapes manufactured by United Aircraft Research Laboratory and purchased from Hamilton Standard; volume %age determined by leaching method indicates the tape contains 49.1 volume % Borsic filaments, 23.6 volume % titanium and 27.3 volume % aluminum; tapes were consolidated into panels at 900 F and 10000 psi for times ranging from one to three hours; data extracted from figure.	Hertz, J., et al. 1972
	142	418.		
	252	741.		
	296	853.		
	324	900.		
	347	929.		
	361	950.		
	391	958.		
	416	962.		
	442	975.		
	474	996.		
	510	1029.		
	557	1109.		
	583	1167.		
	637	1355.		

TABLE 16. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FIBER, TITANIUM/ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	c_p	SPECIFIC HEAT (cont.)	
2 [1]	88 297 450 644	252. 703. 962. 1320.	Borsic (trademark of the Hamilton Standard Division of United Aircraft Corporation for a silicon carbide coated boron filament) titanium/aluminum matrix, borsic 0.1 mm diameter, 49.1 volume %; β-3 titanium 0.025 mm foil, 23.6 volume %; aluminum-6061 sheet 27.3 volume %, unidirectional layup, diffusion bonding of plasma sprayed tapes, sheet thickness 1.02 mm, density 3.12 g cm^{-3}; below room temperature, dynamic heating method and drop calorimeter above room temperature was used; data extracted from table.	Christian, J. L., and Campbell, M. D., 1973

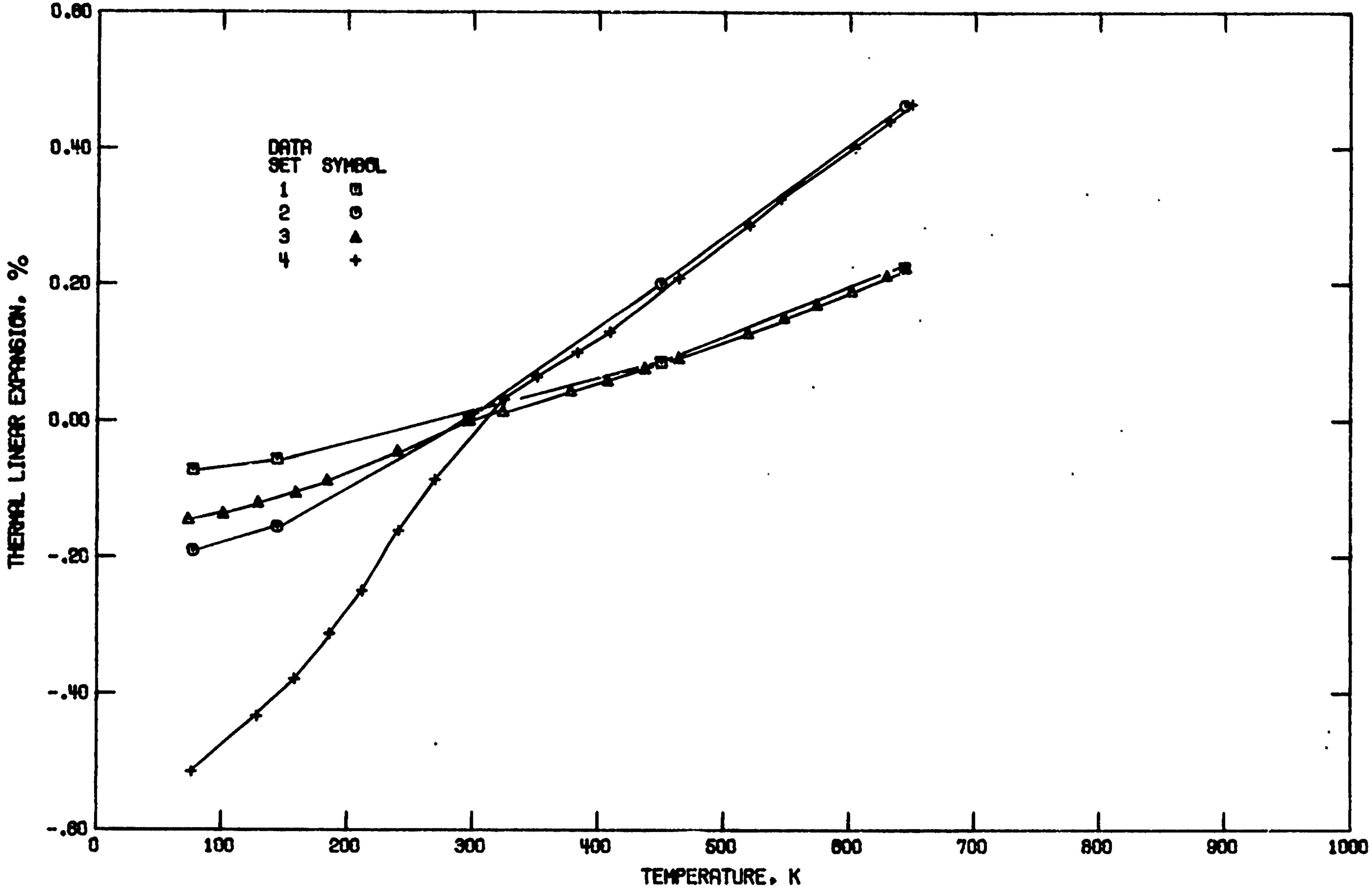

FIGURE 23. THERMAL LINEAR EXPANSION OF BORSIC FIBER.
TITANIUM/ALUMINUM-6061 MATRIX COMPOSITE.

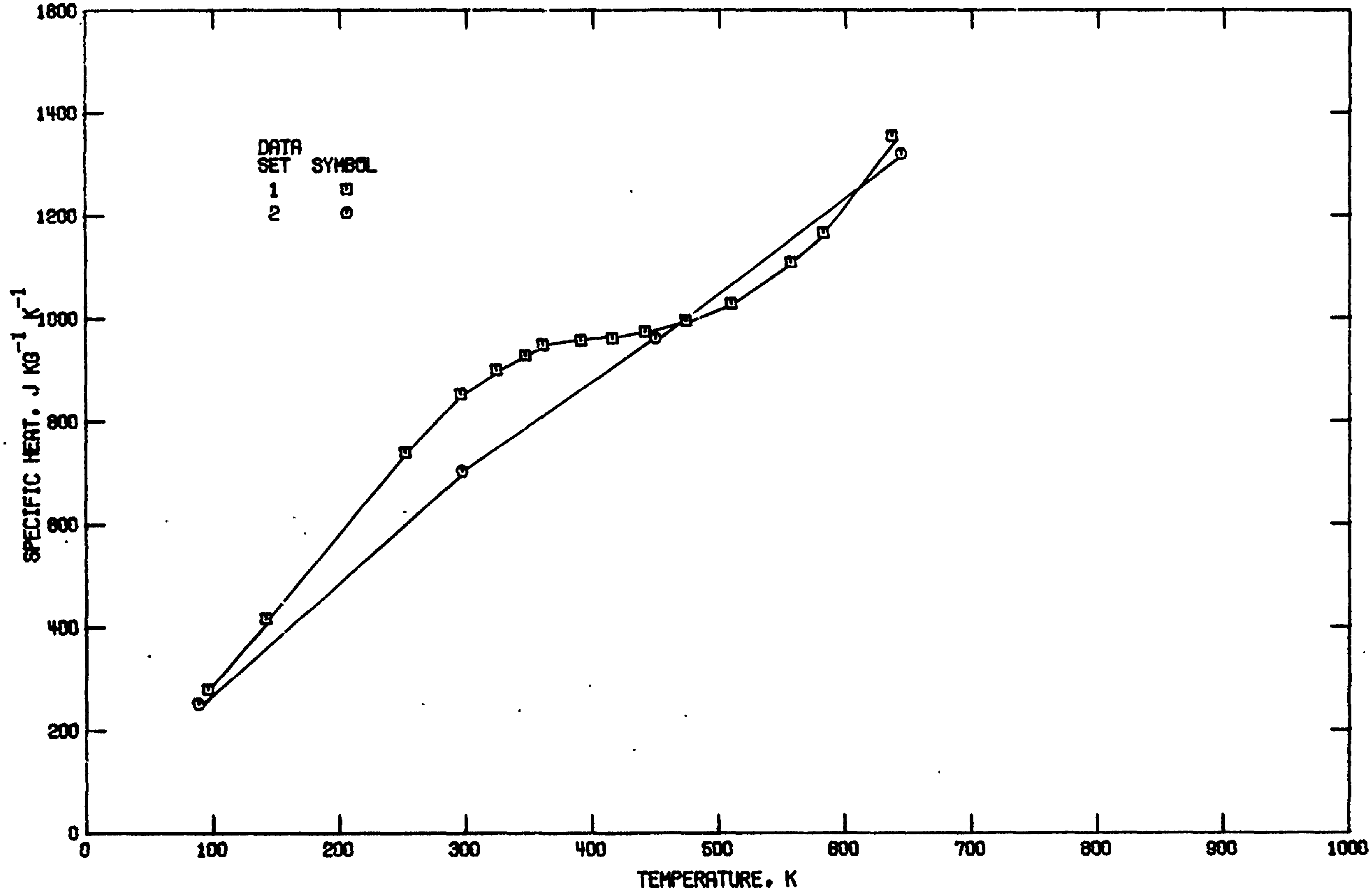

FIGURE 24. SPECIFIC HEAT OF BORSIC FIBER, TITANIUM/ALUMINUM-6061 MATRIX COMPOSITE.

1.16. BORSIC FIBER, AM 355 STAINLESS STEEL/ALUMINUM-6061 MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Hertz et al. [1] and Christian and Campbell [2] reported thermal expansion of a composite made from Borsic/aluminum-6061 plasma-sprayed and Borsic/aluminum-6061 diffusion-bonded material and stainless steel/aluminum-6061 diffusion-bonded monolayer sheet material. Thermal expansion of a well-processed composite containing 42.1 volume percent Borsic fibers and 5.6 volume percent stainless steel wires is about 0.192% and 0.675% near 646 K, respectively, along axial and transverse directions. No attempt is made to reconcile different values of thermal expansion below 293 K reported in these two references.

SPECIFIC HEAT

Christian and Campbell [1] and Hertz et al. [2] reported specific heat data for a 52.3 volume percent aluminum-6061, 42.1 volume percent 0.1 mm Borsic fibers, and 5.6 volume percent 0.05 mm AM 355 stainless steel wire composite made by plasma spraying Borsic/Al-6061 and diffusion bonding AM 355 stainless steel/Al-6061 tapes. Specific heat values range from 339 J kg^{-1} K^{-1} at 89 K to 1314 J kg^{-1} K^{-1} at 642 K [2].

REFERENCES

1. Christian, J.L. and Campbell, M.D., Proc. Cryogen. Eng. Conf., 175-83, 1973.

2. Hertz, J., Christian, M.D., Varlas, M., et al., U.S. Air Force Rept. AFML-TR-71, Vol. 2, 394 pp., 1972. [AD-893 715]

TABLE 17. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FIBER, AM 355 STAINLESS STEEL/ALUMINUM-6061 MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %; Specific Heat, c_p, J Kg^{-1} K^{-1}]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	77 144 297 450 644	-0.294 -0.234 0.006 * 0.297 0.774	Borsic (trademark of the Hamilton Standard Division of United Aircraft Corporation for a silicon carbide coated boron filament)/stainless steel/aluminum matrix, borsic 0.1 mm diameter 42.1 volume %; AM 355 stainless steel 0.05 mm wire, 5.6 volume %; aluminum-6061 sheet, 52.3 volume %, Cross-plied Borsic at 0°; stainless steel at 90° layup; diffusion bonding of plasma-sprayed BORSIC/Al-6061 and diffusion bonded SS/Al-6061 tapes; sheet thickness 1.02 mm; density 2.98 g/cc; measurements in transverse direction; quartz tube dilatometer; values calculated from tabulated values of the mean coefficient and additional information obtained from authors.	Christian, J. L. and Campbell, M. D., 1973
2 [1]	77 144 297 450 644	-0.083 -0.063 0.002 * 0.092 0.199	Borsic (trademark of the Hamilton Standard Division of United Aircraft Corporation for a silicon carbide coated boron filament)/stainless steel/aluminum matrix, borsic 0.1 mm diameter 42.1 volume %; AM 355 stainless steel 0.05 mm wire, 5.6	Christian, J. L. and Campbell, M. D. 1973

TABLE 17. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FIBER, AM 355 STAINLESS STEEL/ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
2 (cont.) [1]			volume %; aluminum-6061 sheet, 52.3 volume %, Cross-plied Borsic at 0°; stainless steel at 90° layup; diffusion bonding of plasma-sprayed BORSIC/Al-6061 and diffusion bonded SS/Al-6061 tapes; sheet thickness 1.02 mm; density 2.98 g/cc; measurements in longitudinal direction; quartz tubedilatometer; values calculated from tabulated values of mean coefficients and additional information obtained from authors.	
3 [2]	78	-0.175	n Borsic/stainless/aluminum-6061 panels made from borsic/aluminum-6061 plasma sprayed and Borsic/aluminun-6061 diffusion bonded material and stainless steel/aluminum-6061 diffusion bonded monolayer sheet material, tape manufactured by Amercom; panels were laid up with five layers of diffusion bonded Borsic/aluminum-6061 monolayer sheet sandwitched between outside layers of stainless steel/aluminum-6061 diffusion bonded monolayer sheet. This is equivalent of eight layers of Borsic	Hertz, J., et al., 1972
	132	-0.141		
	184	-0.095		
	214	-0.071		
	274	-0.019		
	293	0.000		
	349	0.037		
	378	0.056		
	405	0.071		
	436	0.083		
	464	0.100 *		
	492	0.110		
	520	0.121 *		
	546	0.135		
	572	0.151 *		

TABLE 17. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FIBER, AM 355 STAINLESS STEEL/ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
3 (cont.) [2]	602	0.166	filament since two layers of stainless steel wire (0.002 inch diameter) are equivalent to one layer of Borsic fiber (0.004 inch diameter); panels consolidated by one hour soak at 900°F and 3000 psi pressure and 30 minutes at 975°F at 3000 psi; panel contains 42.1 volume % Borsic filaments; 5.9 volume % stainless steel wires; expansion in 0° direction (longitudinal); dilatometry; data extracted from figure.	
	633	0.184		
	647	0.192 *		
4 [2]	84	−0.752	n Similar to the above except expansion in the 90° direction (transverse).	Hertz, J., et al., 1972
	135	−0.644		
	164	−0.566		
	189	−0.466 *		
	221	−0.361		
	271	−0.120		
	300	0.009 *		
	329	0.039		
	383	0.150		
	412	0.204		
	465	0.327		
	491	0.387		
	520	0.453		
	548	0.507		
	574	0.561		

TABLE 17. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FIBER, AM 355 STAINLESS STEEL/ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
4 (cont.) [2]	604	0.612		
	632	0.660		
	646	C.675		
	T	c_p	SPECIFIC HEAT	
1 [2]	89	339.	Borsic/stainless steel/aluminum-6061 panels made from Borsic/aluminum-6061 plasma sprayed and Borsic/aluminum-6061 diffusion bonded and stainless steel/aluminum-6061 diffusion bonded sheet metal; tape manufactured by Amercom; panels were laid up with fine layers of diffusion bonded Borsic/aluminum-6061 monolayer sheet sandwitched between outside layer of stainless steel/aluminum-6061 diffusion bonded monolayer sheet. This is equivalent of eight layers of Borsic filament since two layers of stainless steel wire (0.002 inch diameter) are equivalent to one layer of Borsic fiber (0.004 inch diameter); panels consolidated by one hour soak at 900° F and 3000 psi pressure and 30 minutes at 975° F at 3000 psi; panels contains 42.1 volume % Borsic filaments; 5.6 volume %; data extracted from figure.	Hertz, J., et al., 1972
	145	519.		
	205	699.		
	255	833.		
	317	958.		
	368	1042.		
	430	1117.		
	478	1146.		
	539	1188.		
	588	1238.		
	642	1314.		

TABLE 17. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FIBER, AM 355 STAINLESS STEEL/ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	c_p	SPECIFIC HEAT (cont.)	
2 [1]	88	335.	Borsic (trademark of the Hamilton Standard Division of United Aircraft Corporation for a silicon carbide coated boron filament)/stainless steel/aluminum matrix, borsic 0.1 mm diameter 42.1 volume %; AM 355 stainless steel 0.05 mm wire, 5.6 volume %; aluminum-6061 sheet, 52.3 volume %, Cross-plied Borsic at 0°; stainless steel at 90° layup; diffusion bonding of plasma-sprayed BORSIC/Al and diffusion bonded SS/Al tapes; sheet thickness 1.02 mm; density 2.98 g cm^{-3}; below room temperature dynamic heating method and drop calorimeter above room temperature was used; data extracted from table.	Christian, J. L. and Campbell, M. D., 1973
	297	940.		
	450	1150.		
	644	1340.		

*Not shown in figure.

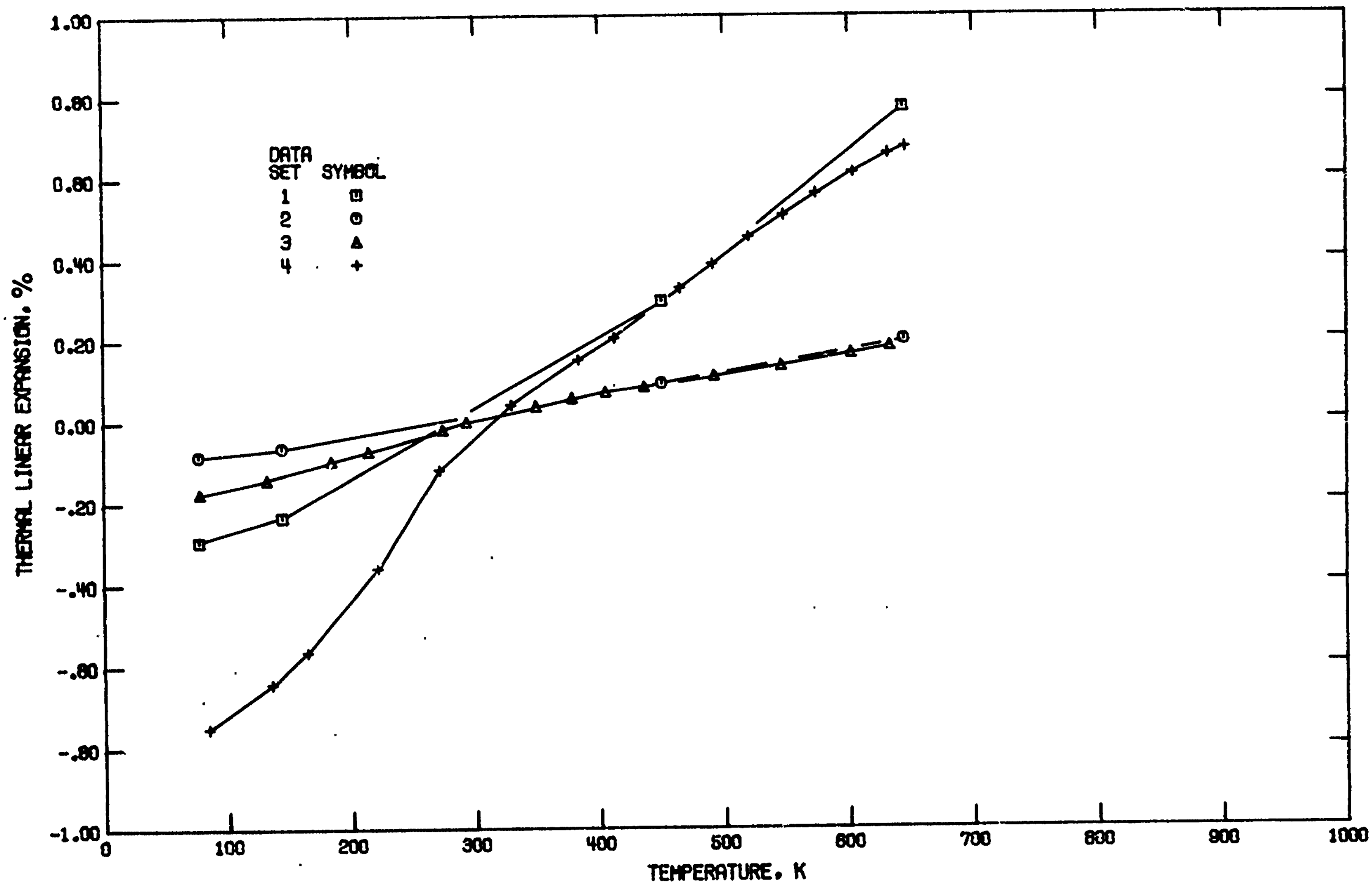

FIGURE 25. THERMAL LINEAR EXPANSION OF BORSIC FIBER, AM 355 STAINLESS STEEL/ALUMINUM-6061 MATRIX COMPOSITE.

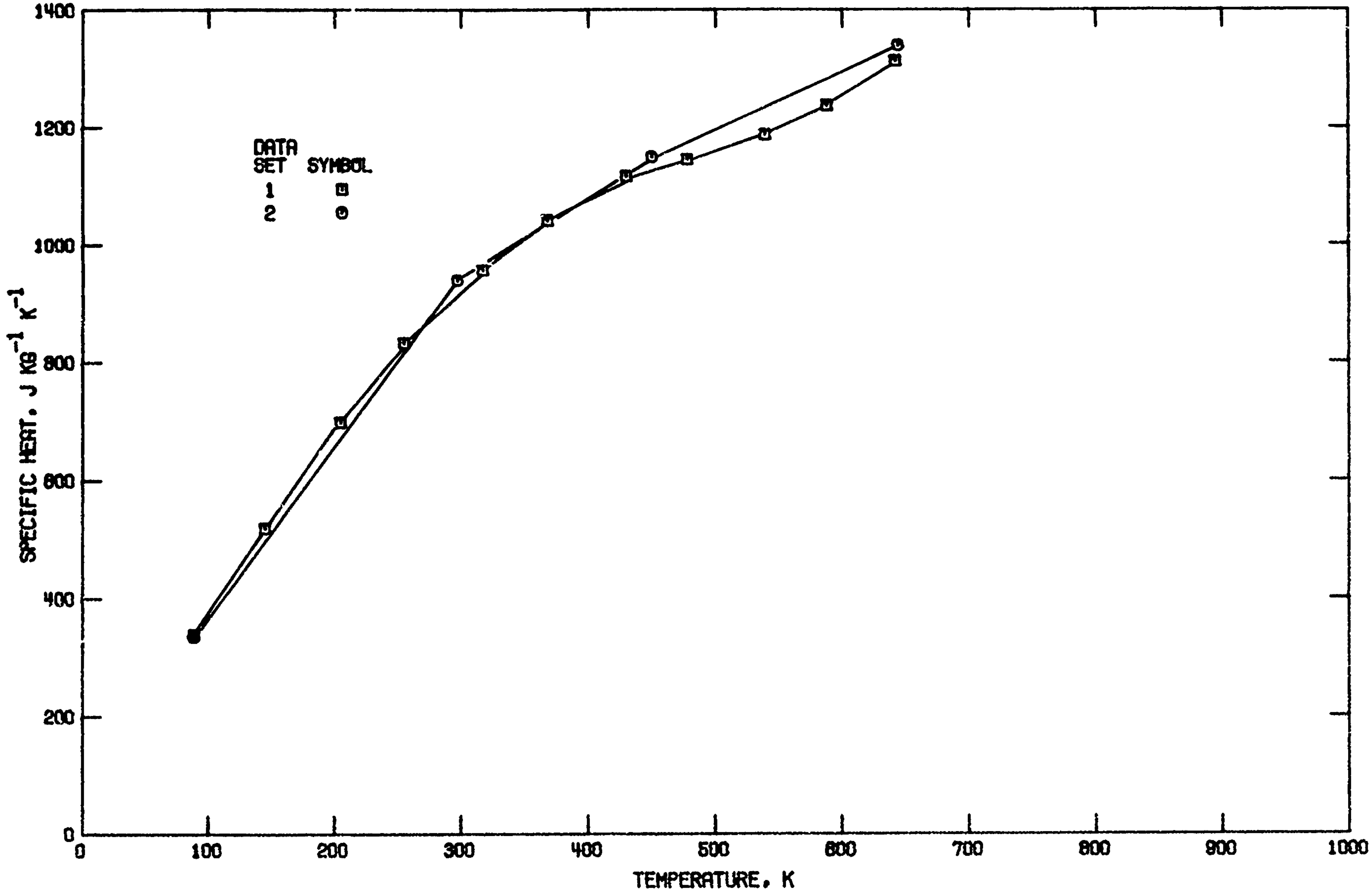

FIGURE 26. SPECIFIC HEAT OF BORSIC FIBER, AM 355 STAINLESS STEEL/ALUMINUM-6061 MATRIX COMPOSITE.

1.17. GRAPHITE FIBER, ALUMINUM-6061 MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Gigerenzer and Strempek [1] reported data for a composite containing 40 volume percent T50 graphite fibers in an aluminum-6061 matrix. This composite contracts 0.027% at 873 K.

THERMAL CONDUCTIVITY

There is one reference [2] in which the thermal conductivity of graphite fiber aluminum-6061-0 matrix composite is reported. The data are for a 3-ply panel with graphite fibers coated with nickel before being consolidated into the composite, and for heat flow in a direction perpendicular to the fibers only.

REFERENCES

1. Gigerenzer, H. and Strempek, G.C., Army Materials Mechanics Research Center Rept. AMMC-CTR-76-19, 29 pp., 1976. [AD-A031 437]
2. O'Kelly, K.P., NASA Rept. NASA-CR-115221, 79 pp., 1971. [N72-11432]

TABLE 18. DATA ON THE THERMOPHYSICAL PROPERTIES OF GRAPHITE FIBER, ALUMINUM-6061 MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %; Thermal Conductivity, λ, W m^{-1} K^{-1}]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	298	0.000	Single strand T50 graphite/aluminum-6061 composite wire produced by optimizing parameters in the Lachman Coating process in conjunction with an aluminum-6061 melt infiltration process; 40 volume % fibers; measurements from Aerospace Corporation; data points extracted from figure.	Gigerenzer, H. and Strempek, G. C., 1976
	373	0.000		
	473	0.000		
	573	-0.010		
	673	-0.016		
	773	-0.021		
	873	-0.027		
	T	λ	THERMAL CONDUCTIVITY	
1 [2]	121	81.4	Graphite filaments were first heat-cleaned in a vacuum diffusion furnace with an inert atmosphere at 1500°F for 1 hour, sensitized by immersion in a mixture of stannous chloride and hydrochloric acid for 1 minute, activation- treated by immersion in a mixture of palladium chloride and hydrochloric acid for 1 minute, and nickel coated by immersion in a mixture of standard "electroless" nickel solution (McDermit proprietary solution) at 120 to 180°F; the graphite tow (Morganite high modulus graphite, 0.0002 in diameter) were pressed	O'Kelly, K. P., 1971
	170	84.6		
	249	89.1		
	373	91.8		
	421	92.7		

TABLE 18. DATA ON THE THERMOPHYSICAL PROPERTIES OF GRAPHITE FIBER, ALUMINUM-6061 MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
1 (cont.) [2]			bonded to aluminum 6061-0 sheet into monolayer tapes; the specimen was made of three plys of tape, with 0.001 in silicon/aluminum foils placed between the plys and at the surface; fiber volume fraction ~50%; heat flow in the plane of panel and perpendicular to fiber direction.	

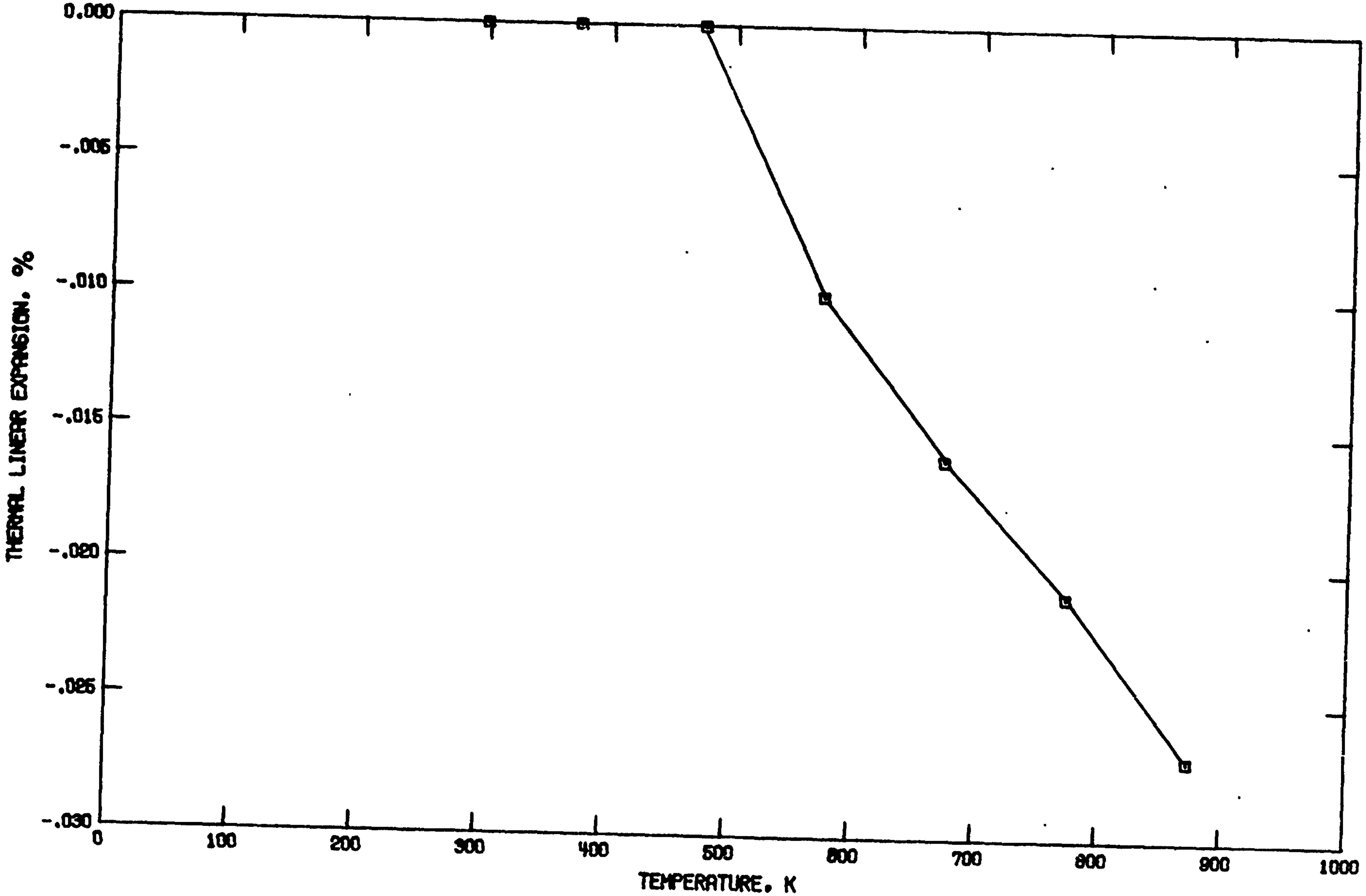

FIGURE 27. THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, ALUMINUM-6061 MATRIX COMPOSITE.

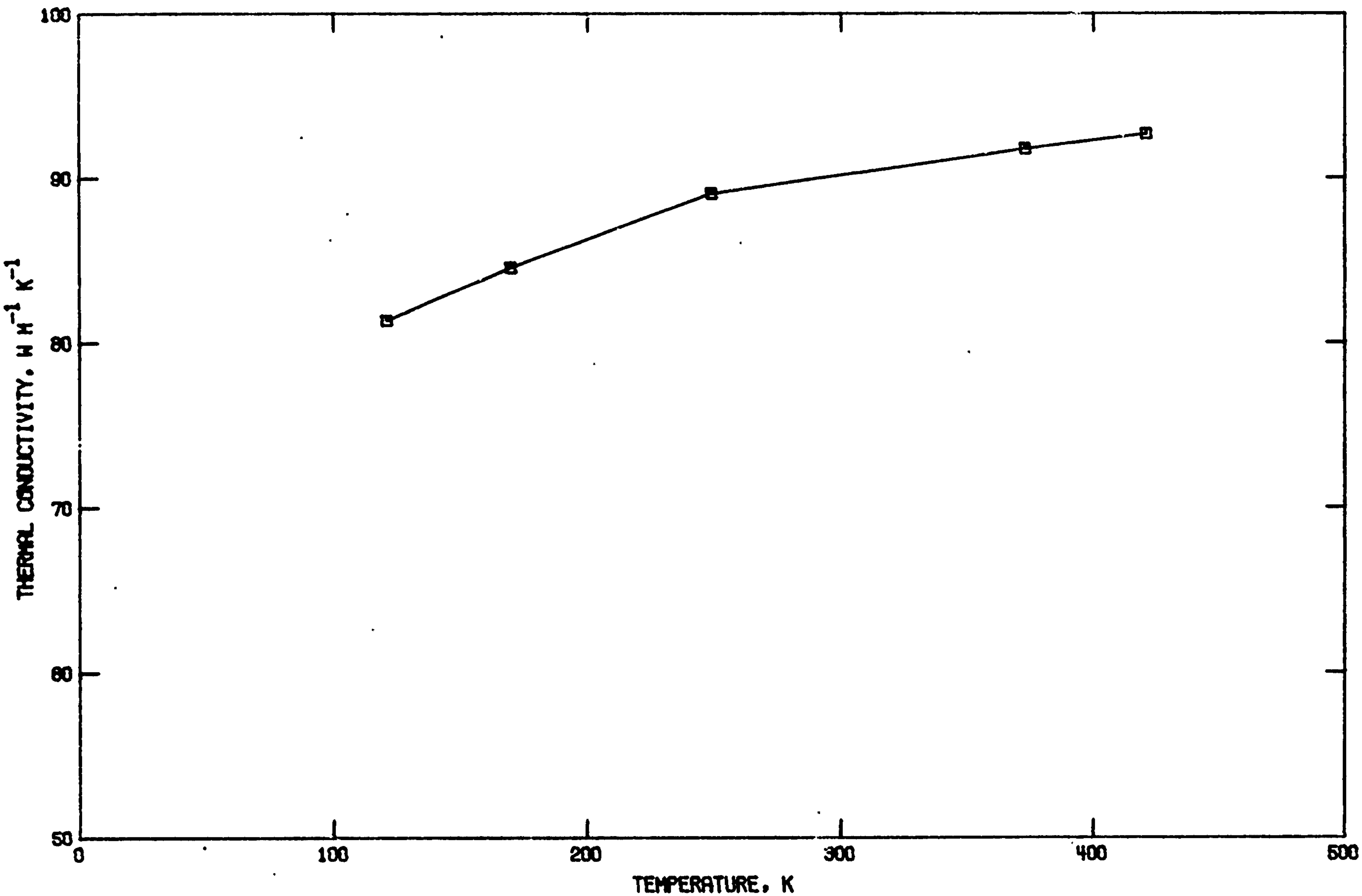

FIGURE 28. THERMAL CONDUCTIVITY OF GRAPHITE FIBER, ALUMINUM-6061 MATRIX COMPOSITE.

1.18. BERYLLIUM WIRE, ALUMINUM-7002 MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Gerdeman et al. [1] reported thermal expansion data for 26 volume percent beryllium wires in an aluminum-7002 matrix. The data are on several diffusion-bonded specimens during heating and cooling. No apparent anomalies were observed and the measurement direction is not reported.

REFERENCE

1. Gerdeman, D.A., Wurst, J.C., Cherry, J.A., and Berner, W.E., U.S. Air Force Rept. AFML-TR-6853, 94 pp., 1968. [AD-835 768]

TABLE 19. DATA ON THE THERMAL LINEAR EXPANSION OF BERYLLIUM WIRE, ALUMINUM-7002 MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	293	0.000	Composite consisted of 0.005 inch diameter 26 volume % beryllium wires in Al-7002 matrix; two layers of total 0.02 inch thickness; diffusion bonded for four hours at 3600 psi and 900°F; quartz dilatometer; measurements on several samples during both heating and cooling cycles which was repeated at least twice; Leitz dilatometer; results of run No. 1; measurement direction not reported; data extracted from figure.	Gerdeman, D. A., Wurst, J. C., Cherry, J. A., and Berner, W. E., 1968
	310	0.013		
	366	0.056		
	421	0.093		
	476	0.132		
	532	0.169		
	587	0.191		
2 [1]	293	0.000	Similar to the above except results of run No. 2.	Gerdeman, D. A., et al., 1968
	310	0.009		
	366	0.048		
	422	0.089		
	476	0.131		
	532	0.176		
	587	0.210		

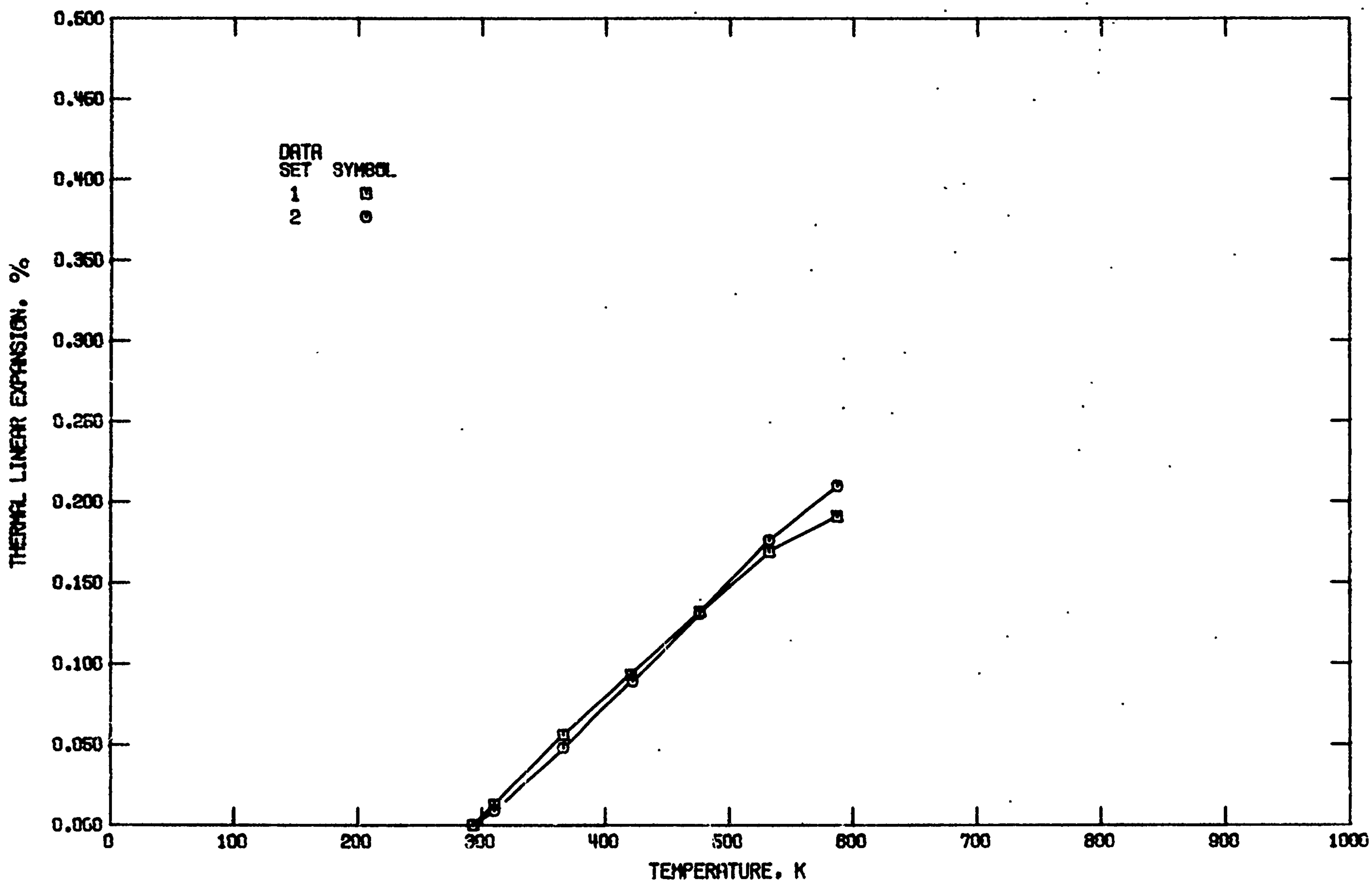

FIGURE 29. THERMAL LINEAR EXPANSION OF BERYLLIUM WIRE. ALUMINUM-7002 MATRIX COMPOSITE.

1.19. SiC WHISKER, Al-5.5Cu MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Barr [1] reported thermal expansion data for a hot pressed composite containing 20 volume percent SiC whiskers. Fairly consistent results were obtained for their cooling and heating measurements. The measurement direction is not reported.

REFERENCE

1. Barr, H.N., U.S. Air Force Rept. AFML-TR-67-296, 67 pp., 1967. [AD-827 531]

TABLE 20. DATA ON THE THERMAL LINEAR EXPANSION OF SiC WHISKER, Al-5.5Cu MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	291	-0.001	SiC whiskers carborundum RS grade and Al-4 (5.5 atomic %) Cu powder hot pressed as follows: heat the die and extrusions slowly in air to 400°C for 15 minutes, then cooled, the die was then heated slowly to the hot press temperature, 550-575°C; then pressure of 2-8 tons per square inch was applied to die for 30 minutes, then allowed to cool under pressure; 20 volume % SiC whiskers; thermal expansion measured in air; heating cycle, data extracted from figure.	Barr, H. N., 1967
	332	0.060		
	364	0.113		
	433	0.232		
	455	0.271		
	469	0.293 *		
	489	0.323		
	508	0.348		
	535	0.383		
	563	0.419		
	599	0.458 *		
	631	0.493		
	662	0.530 *		
	694	0.570		
	728	0.614 *		
	758	0.660		
	786	0.704		
	834	0.795		
2 [1]	294	0.003 *	Similar to the above except cooling cycle.	Barr, H. N., 1967
	306	0.020		
	320	0.081		
	346	0.113		
	364	0.136		
	382	0.158		
	400	0.186		
	417	0.211		

TABLE 20. DATA ON THE THERMAL LINEAR EXPANSION OF SiC WHISKER, Al-5.5Cu MATRIX COMPOSITE

(continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
2 (cont.) [1]	436	0.240 *		
	474	0.299		
	525	0.372		
	577	0.435		
	605	0.467		
	667	0.532		
	702	0.573 *		
	736	0.613		
	791	0.693		
	827	0.774		

*Not shown in figure.

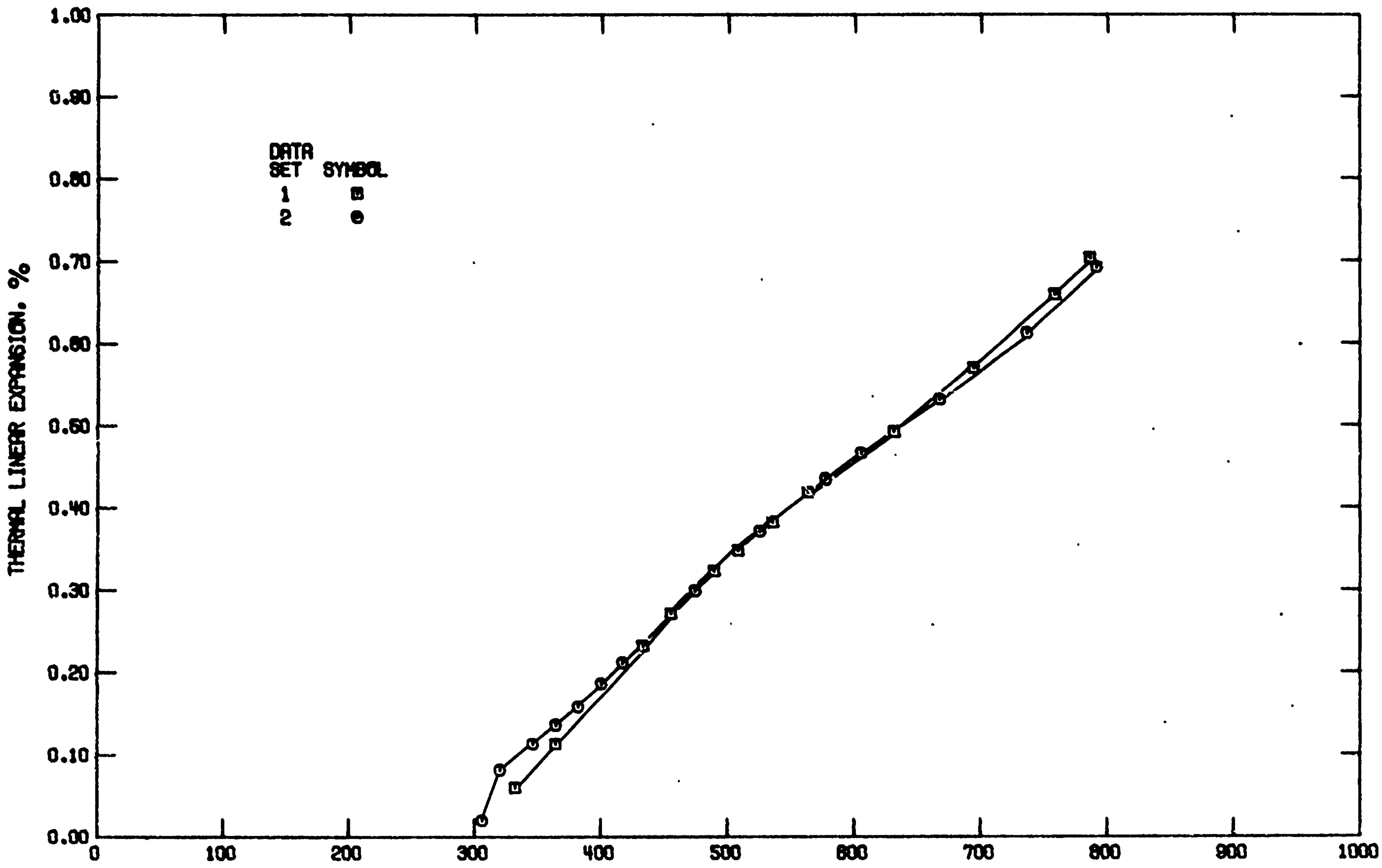

FIGURE 30. THERMAL LINEAR EXPANSION OF SIC WHISKER, AL-5.5 CU MATRIX COMPOSITE.

CHAPTER 2

COPPER AND COPPER ALLOY MATRIX COMPOSITES

2.1. BORON FIBER, COPPER MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Wolff and Hill [1] reported thermal expansion data for three composites of densities from 452- 491 lb ft^{-3} and containing 10 volume percent continuous aligned fibers. Percent thermal expansion value at about 589°F drops from 0.466 for a composite with density 452 lb ft^{-3} to 0.310 for a composite with density 491 lb ft^{-3}. They also reported thermal expansion data for 10-30 volume percent discontinuous aligned boron fibers composites of densities 448-488 lb ft^{-3}. In general, composites with continuous aligned fibers exhibit lower expansion than those with discontinuous aligned fibers.

ELECTRICAL RESISTIVITY

Only two data sets on the electrical resistivity of copper-boron composites are available as a function of temperature from 294 to 1100 K for 5.9% and 6.4% boron fiber volume [2]. The electrical resistivity increases with an increase in temperature.

REFERENCES

1. Wolff, E.G. and Hill, R.J., U.S. Air Force Rept. AFML-TR-67-140, 163 pp., 1967. [AD-816 439]
2. Tye, R.P., Hayden, R.W., and Spinney, S.C., High Temp.-High Pressures, 4, 503-11, 1972.

TABLE 21. DATA ON THE THERMAL LINEAR EXPANSION AND ELECTRICAL RESISTIVITY OF BORON FIBER, COPPER MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %; Electrical Resistivity, ρ, 10^{-8} Ω m]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	293	0.000	Copper with continuous aligned boron fibers, 10 volume % boron fibers, density 452 lb ft^{-3}, quartz tube dilatometer; measurement direction not reported; values calculated from tabulated values of mean coefficient.	Wolff, E. G., and Hill, R. J., 1967
	355	0.073		
	405	0.179		
	589	0.466		
2 [1]	293	0.000	Similar to the above except density 462 lb ft^{-3}.	Wolff, E. G., and Hill, R. J., 1967
	433	0.166		
	505	0.279		
	589	0.361		
3 [1]	293	0.000	Similar to the above except density 491 lb ft^{-3}.	Wolff, E. G., and Hill, R. J., 1967
	377	0.115		
	444	0.144		
	589	0.310		
4 [1]	293	0.000	Similar to the above except density 563 lb ft^{-3}.	Wolff, E. G., and Hill, R. J., 1967
	405	0.174		
	466	0.282		
	589	0.473		
5 [1]	293	0.000	Similar to the above except discontinuous aligned boron fibers; density 448 lb ft^{-3}.	Wolff, E. G., and Hill, R. J., 1967
	422	0.176		
	533	0.355		
	589	0.434		
6 [1]	293	0.000	Similar to the above except density 488 lb ft^{-3}.	Wolff, E. G., and Hill, R. J., 1967
	450	0.262		

TABLE 21. DATA ON THE THERMAL LINEAR EXPANSION AND ELECTRICAL RESISTIVITY OF BORON FIBER, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
7 [1]	293 450	0.000 0.262	Similar to the above.	Wolff, E. G., and Hill, R. J., 1967
8 [1]	293 422	0.000 0.193	Similar to the above except 30 volume % boron fibers; density 468 lb ft^{-3}.	Wolff, E. G., and Hill, R. J., 1967
9 [1]	293 400	0.000 0.134	Similar to the above except density 444 lb ft^{-3}.	Wolff, E. G., and Hill, R. J., 1967
	T	ρ	ELECTRICAL RESISTIVITY	
1 [2]	294 300 400 500 600 700 800 900 1000 1100	2.73 2.81 3.81 4.83 5.86 6.94 8.05 9.21 10.48 11.78	93.5 Cu, 5.9B; formed from copper powder >99.5% pure and B powder, total B 95.65%; is statically pressed and extruded; density 7270-7340 Kg/m^3.	Tye, R. P., Hayden, R. W., and Spinney, S. C., 1972
2 [2]	294 300 400 500 600 700 800 900 1000 1100	3.02 3.10 4.22 5.31 6.41 7.56 8.72 9.88 11.18 12.55	93.5 Cu, 6.4 B; formed from copper powder >99.5% pure and B powder total B 90.47%; is statically pressed and extruded; density 7130-7210 Kg/m^3.	Tye, R. P., et al., 1972

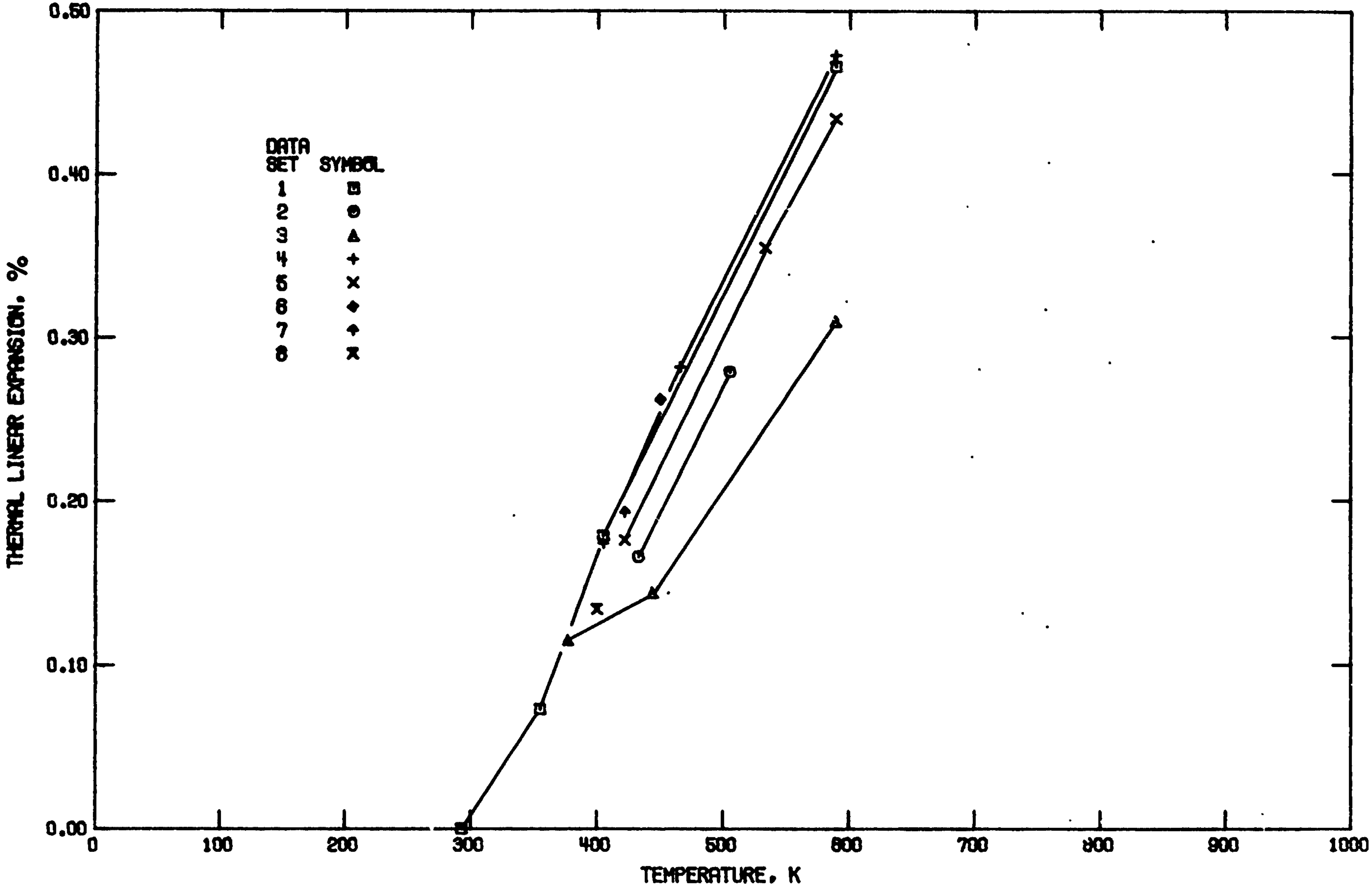

FIGURE 31. THERMAL LINEAR EXPANSION OF BORON FIBER. COPPER MATRIX COMPOSITE.

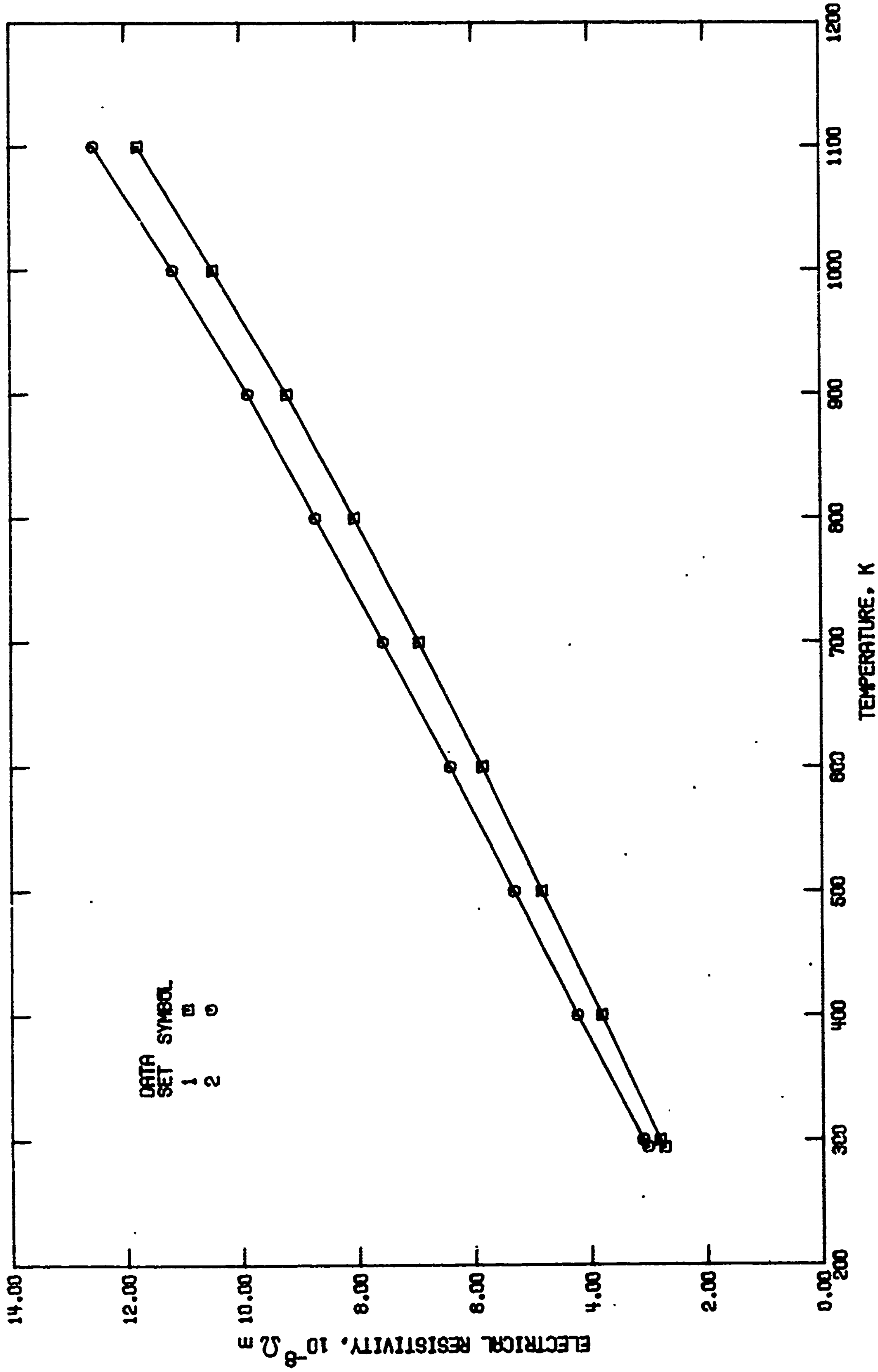

FIGURE 32. ELECTRICAL RESISTIVITY OF BORON FIBER, COPPER MATRIX COMPOSITE.

2.2. CARBON FIBER, COPPER MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Busalov et al. [1] reported thermal expansion data for 30 volume percent carbon fibers in a copper matrix. Some of their observations are as follows. Thermal expansion of this composite is fairly linear up to 150-200°C, and above 600°C it starts to contract which is explained as due to the negative thermal expansion coefficient of carbon fibers and also due to the increased yield stress of the matrix. The data show that the thermal expansion of the specimen in the transverse direction is much higher and is fairly proportional to the temperature up to 700°C. Even after more heating cycles the specimen did not show any permanent shrinkage in the transverse direction, and the expansion was independent of the fiber content.

REFERENCE

1. Busalov, Yu.E., Kop'ev, I.M., Pompe, W., Voel'mar, S., and Winkler, I., Fiz. Khim. Obrab. Mater., (4), 107-11, 1978.

TABLE 22. DATA ON THE THERMAL LINEAR EXPANSION OF CARBON FIBER, COPPER MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	274	-0.017	Composites with 30 volume % carbon fibers made by hot pressing metallized bundles of carbon fibers; it had tensile strength of 30-40 $kgmm^{-2}$; modulus of elasticity of 9000-11000 $kgmm^{-2}$ and 1.5° deformation at rupture; first heating cycle in the longitudinal direction; data extracted from figure; zero point correction is -0.016%.	Busalov, Yu, Ye., Kop'yev, I. M., Pompe, V., Vel'mar, S., and Vinkler, I., 1978
	339	0.051		
	370	0.068		
	425	0.094		
	471	0.105		
	526	0.106		
	571	0.104		
	607	0.096		
	641	0.082		
	670	0.064		
	728	0.034		
	772	0.012		
	826	-0.011		
	874	-0.007		
	915	0.013		
	961	0.045		
2 [1]	295	0.001	Similar to the above except first cooling in the longitudinal direction; data extracted from figure; zero point correction is 0.244%.	Busalov, Yu, Ye., et al., 1978
	373	0.028		
	472	0.052		
	569	0.081		
	615	0.089		
	670	0.105		
	721	0.123		
	773	0.142		
	871	0.171		
	907	0.182		
	961	0.182		

TABLE 22. DATA ON THE THERMAL LINEAR EXPANSION OF CARBON FIBER, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
3 [1]	274	-0.017	Similar to the above except second heating cycle in the longitudinal direction; data extracted from figure; zero point corrections -0.018%.	Busalov, Yu, Ye., et al., 1978
	326	0.040		
	372	0.084		
	435	0.133		
	473	0.162		
	519	0.188		
	570	0.204		
	621	0.209		
	669	0.205		
	703	0.200		
	743	0.175		
	773	0.152		
	820	0.105		
	872	0.029		
	912	-0.012		
	972	-0.061		
4 [1]	295	0.001	Similar to the above except cooling cycle; data extracted from figure; zero point correction is 0.244%.	Busalov, Yu, Ye., et al., 1978
	373	0.002		
	417	0.003		
	474	0.008		
	525	0.014		
	569	0.025		
	671	0.054		
	774	0.088		
	871	0.118		
	945	0.147		

TABLE 22. DATA ON THE THERMAL LINEAR EXPANSION OF CARBON FIBER, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
5 [1]	273	−0.023	Similar to the above except heating cycle in the longitudinal direction after annealing; zero point correction is −0.024%.	Busalov, Yu, Ye., et al., 1978
	334	0.021		
	370	0.047		
	427	0.074		
	471	0.094		
	528	0.105		
	568	0.108		
	621	0.104		
	670	0.099		
	725	0.090		
	774	0.083		
	831	0.068		
	873	0.054		
	927	0.026		
	980	−0.009		
6 [1]	292	0.002	Similar to the above except cooling cycle; data extracted from figure; zero point correction is 0.190%.	Busalov, Yu, Ye., et al., 1978
	372	0.007		
	472	0.028		
	569	0.052		
	670	0.087		
	723	0.100		
	771	0.121		
	870	0.163		
	927	0.184		
7 [1]	312	0.002	Similar to the above except first heating cycle of the four repeated cycling; data extracted from figure;	Busalov, Yu, Ye., et al., 1978
	340	0.043		
	368	0.077		

TABLE 22. DATA ON THE THERMAL LINEAR EXPANSION OF CARBON FIBER, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
7 (cont.) [1]	423	0.122	zero point correction is 0.002%.	
	469	0.143		
	491	0.148		
	508	0.145		
8 [1]	314	0.030	Similar to the above except first cooling cycle; data extracted from figure; zero point correction is 0.150%.	Busalov, Yu. Ye., et al., 1978
	319	0.047		
	341	0.086		
	370	0.127		
	387	0.151		
	438	0.218		
	470	0.254		
	489	0.274		
	508	0.293		
9 [1]	314	0.026	Similar to the above except second heating cycle; data extracted from figure; zero point correction is 0.146%.	Busalov, Yu. Ye., et al., 1978
	330	0.043		
	369	0.093		
	407	0.147		
	440	0.196		
	468	0.231		
	501	0.261		
	525	0.272		
	543	0.276		
	551	0.276		
10 [1]	617	0.037	Similar to the above except second cooling cycle; data extracted from figure; zero point correction is 0.222%.	Busalov, Yu. Ye., et al., 1978
	370	0.121		
	397	0.162		

TABLE 22. DATA ON THE THERMAL LINEAR EXPANSION OF CARBON FIBER, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
10 (cont.) [1]	438	0.227		
	470	0.268		
	494	0.296		
	529	0.332		
	551	0.352		
11 [1]	316	0.031	Similar to the above except third heating cycle; data exteacted from figure; zero point correction is 0.216%.	Busalov, Yu, Ye., et al., 1978
	370	0.102		
	420	0.171		
	455	0.221		
	469	0.238		
	496	0.268		
	514	0.287		
	538	0.309		
	551	0.318		
	568	0.326		
	580	0.326		
12 [1]	314	0.047	Similar to the above except third cooling cycle; data extracted from figure; zero point correction is 0.280%.	Busalov, Yu, Ye., et al., 1978
	334	0.082		
	348	0.099		
	370	0.131		
	403	0.176		
	435	0.224		
	468	0.272		
	493	0.306		
	513	0.330		
	538	0.356		
	568	0.381		
	580	0.390		

TABLE 22. DATA ON THE THERMAL LINEAR EXPANSION OF CARBON FIBER, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
[illegible] [1]	314	0.026	Similar to the above except fourth heating cycle; data extracted from figure; zero point correction is 0.256%.	Busalov, Yu, Ye., et al., 1978
	345	0.057		
	370	0.089		
	413	0.157		
	468	0.234		
	488	0.260		
	512	0.286		
	539	0.314		
	568	0.329		
	585	0.333		
	600	0.335		
14 [1]	308	0.022	Similar to the above except fourth cooling cycle; data extracted from figure; zero point correction is 0.316%.	Busalov, Yu, Ye., et al., 1978
	342	0.074		
	369	0.115		
	442	0.216		
	468	0.251		
	520	0.318		
	569	0.372		
	580	0.380		
	597	0.393		
15 [1]	320	0.064	Similar to above except first heating cycle up to 400°C; data extracted from figure; zero point correction is 0.046%.	Busalov, Yu, Ye., et al., 1978
	373	0.155		
	399	0.214		
	424	0.241		
	471	0.301		
	527	0.377		
	570	0.415		

TABLE 22. DATA ON THE THERMAL LINEAR EXPANSION OF CARBON FIBER, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
15 (cont.) [1]	617	0.448		
	647	0.459		
	670	0.453		
16 [1]	314	0.035	Similar to the above except cooling cycle; data extracted from figure; zero point correction is 0.192%.	Busalov, Yu, Ye., et al., 1978
	349	0.100		
	376	0.138		
	414	0.193		
	472	0.263		
	516	0.344		
	570	0.431		
	628	0.513		
	650	0.567		
	670	0.599		
17 [1]	313	0.038	Similar to the above except second heating cycle; data extracted from figure; zero point correction is 0.184%.	Busalov, Yu, Ye., et al., 1978
	346	0.120		
	375	0.179		
	427	0.288		
	471	0.369		
	528	0.445		
	572	0.515		
	622	0.553		
	649	0.564		
	671	0.554		
18 [1]	314	0.035	Similar to the above except second cooling cycle; data extracted from figure; zero point correction is	Busalov, Yu, Ye., et al., 1978
	327	0.057		
	343	0.084		

TABLE 22. DATA ON THE THERMAL LINEAR EXPANSION OF CARBON FIBER, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
18 (cont.) [1]	376	0.122	0.208%.	
	399	0.144		
	436	0.187		
	471	0.252		
	528	0.344		
	572	0.410		
	609	0.464		
	647	0.529		
	670	0.578		
19 [1]	319	0.051	Similar to the above except first heating cycle of the measurement on specimen with orientation 90° relative to the specimen axis; data extracted from figure; zero point correction is 0.024%.	Busalov, Yu. Ye., et al., 1978
	373	0.165		
	430	0.300		
	468	0.392		
	523	0.528		
	569	0.642		
	605	0.739		
	632	0.820		
	660	0.923		
	670	0.971		
20 [1]	314	0.050	Similar to the above except first cooling cycle; data extracted from figure; zero point correction -0.004%.	Busalov, Yu, Ye., et al., 1978
	370	0.180		
	420	0.305		
	468	0.435		
	526	0.597		
	597	0.792		
	646	0.900		
	672	0.943		

TABLE 22. DATA ON THE THERMAL LINEAR EXPANSION OF CARBON FIBER, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
21 [1]	316	0.049	Similar to the above except second heating cycle; data extracted from figure; zero point correction is 0.016%.	Busalov, Yu, Ye., et al., 1978
	371	0.179		
	425	0.314		
	468	0.422		
	518	0.547		
	569	0.683		
	613	0.818		
	643	0.915		
	660	0.975		
	665	1.018		
22 [1]	311	0.044	Similar to the above except second cooling cycle; data extracted from figure; zero point correction is -0.016%.	Busalov, Yu, Ye., et al., 1978
	340	0.114		
	371	0.195		
	421	0.331		
	408	0.455		
	515	0.585		
	568	0.737		
	605	0.840		
	643	0.932		
	665	0.986		

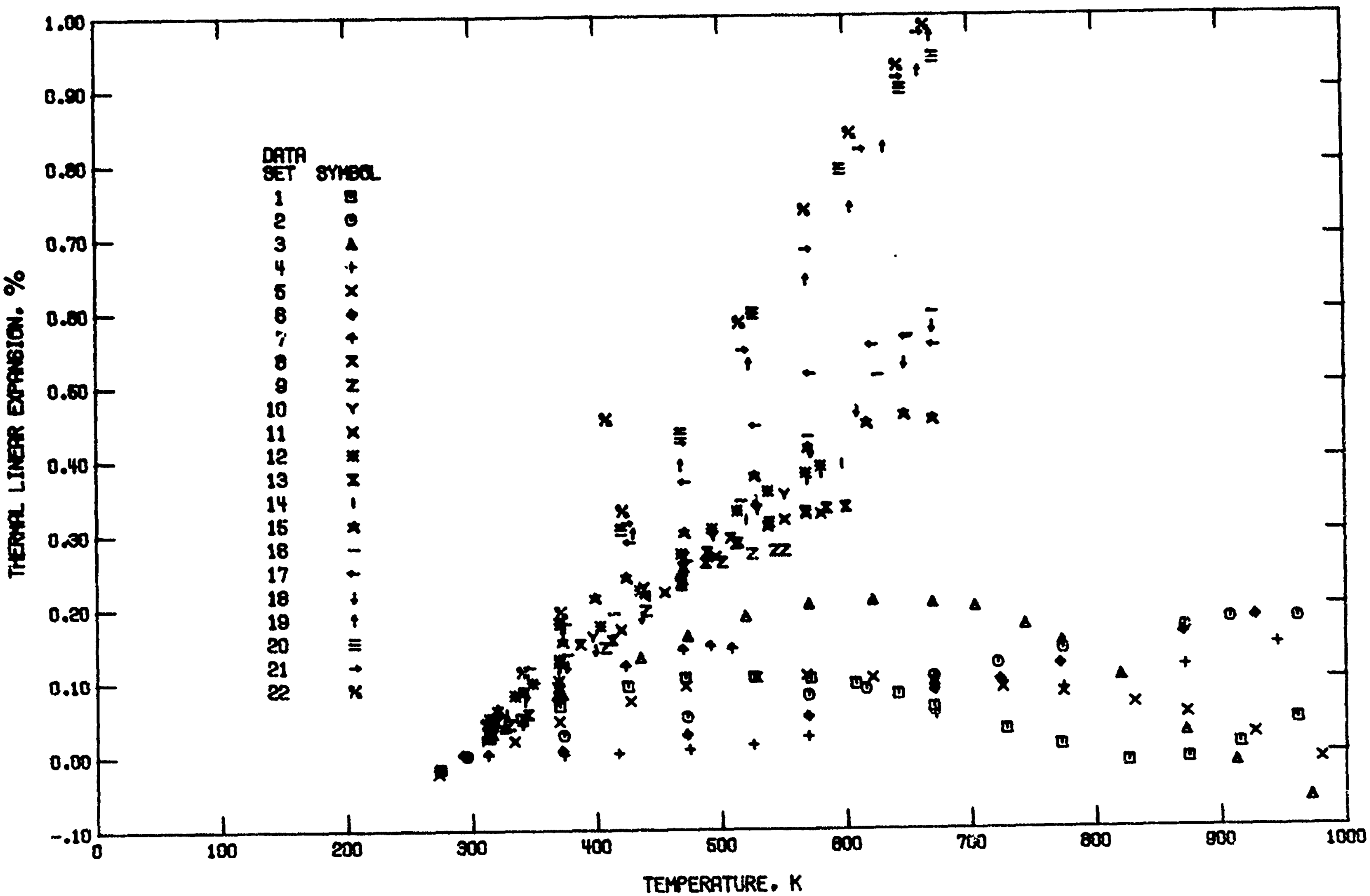

FIGURE 33. THERMAL LINEAR EXPANSION OF CARBON FIBER, COPPER MATRIX COMPOSITE.

2.3. TUNGSTEN FIBER, COPPER MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Salibekov et al. [1] reported thermal expansion data for composite containing 18 volume percent plated tungsten fibers impregnated with molten copper. They [1] also reported the data for a composite containing 12 volume percent tungsten net. Introduction of 18 volume percent tungsten fibers into the copper matrix sharply reduces its thermal expansion. Intensive relaxation of stresses in the matrix begins around 500 K. At about 1073 K, the overall thermal expansion of the composite approaches that of tungsten. Thermal expansion of a composite with 12 volume percent tungsten net differs little from a composite with uniaxial aligned fibers. Thermal expansion of 56 volume percent tungsten fiber composite is almost the same as that of tungsten.

ELECTRICAL RESISTIVITY

There are four data sets on the electrical resistivity of copper matrix with tungsten wires available as a function of volume percent of tungsten wires at 293 K [2]. One data set is for a composite with continuous structure and three are for composites having discrete structure.

REFERENCES

1. Salibekov, S.E., Portnoi, K.I., and Chubarov, V.M., High Temp., 10(4), 702-6, 1972.

2. Rubal'chenko, M.K., Ustinov, L.M., and Zhamnova, V.I., Sov. Powder Met. Metal Ceram., (5), 393-5, 1972.

TABLE 23. DATA ON THE THERMAL LINEAR EXPANSION OF TUNGSTEN FIBER, COPPER MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	293	0.000	18 vol. % tungsten fiber copper matrix composite obtain by vacuum impregnation of plaited tungsten fibers of 0.4 mm diameter with liquid copper; test specimen 30 x 4 x 3 mm plates; heated in argon atmosphere at 3 degrees min^{-1}; accuracy ±5%; dilatometry, heating cycle; measurement direction not reported; data extracted from figure.	Salibekov, S. E., Portnoi, K. I., and Chubarov, V. M., 1972
	295	0.003 *		
	350	0.064		
	430	0.141		
	472	0.170		
	516	0.193		
	577	0.209		
	635	0.218		
	740	0.243		
	817	0.266		
	897	0.294		
	970	0.323		
2 [1]	293	0.000 *	Similar to the above except cooling cycle; zero point correction is 0.04%.	Salibekov, S. E., et al., 1972
	295	0.008 *		
	420	0.081		
	487	0.120		
	567	0.165		
	647	0.203		
	743	0.251 *		
	839	0.293		
	919	0.334		
	989	0.373		
3 [1]	293	0.000 *	Similar to the above except 56 volume % tungsten fibers and heating cycle.	Salibekov, S. E., et al., 1972
	302	0.020		
	417	0.064		

TABLE 23. DATA ON THE THERMAL LINEAR EXPANSION OF TUNGSTEN FIBER, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	<u>THERMAL LINEAR EXPANSION</u> (cont.)	
3 (cont.) [1]	526	0.115		
	612	0.254		
	737	0.205		
	836	0.253		
	919	0.294		
	980	0.323 *		
	1044	0.358		

*Not shown in figure.

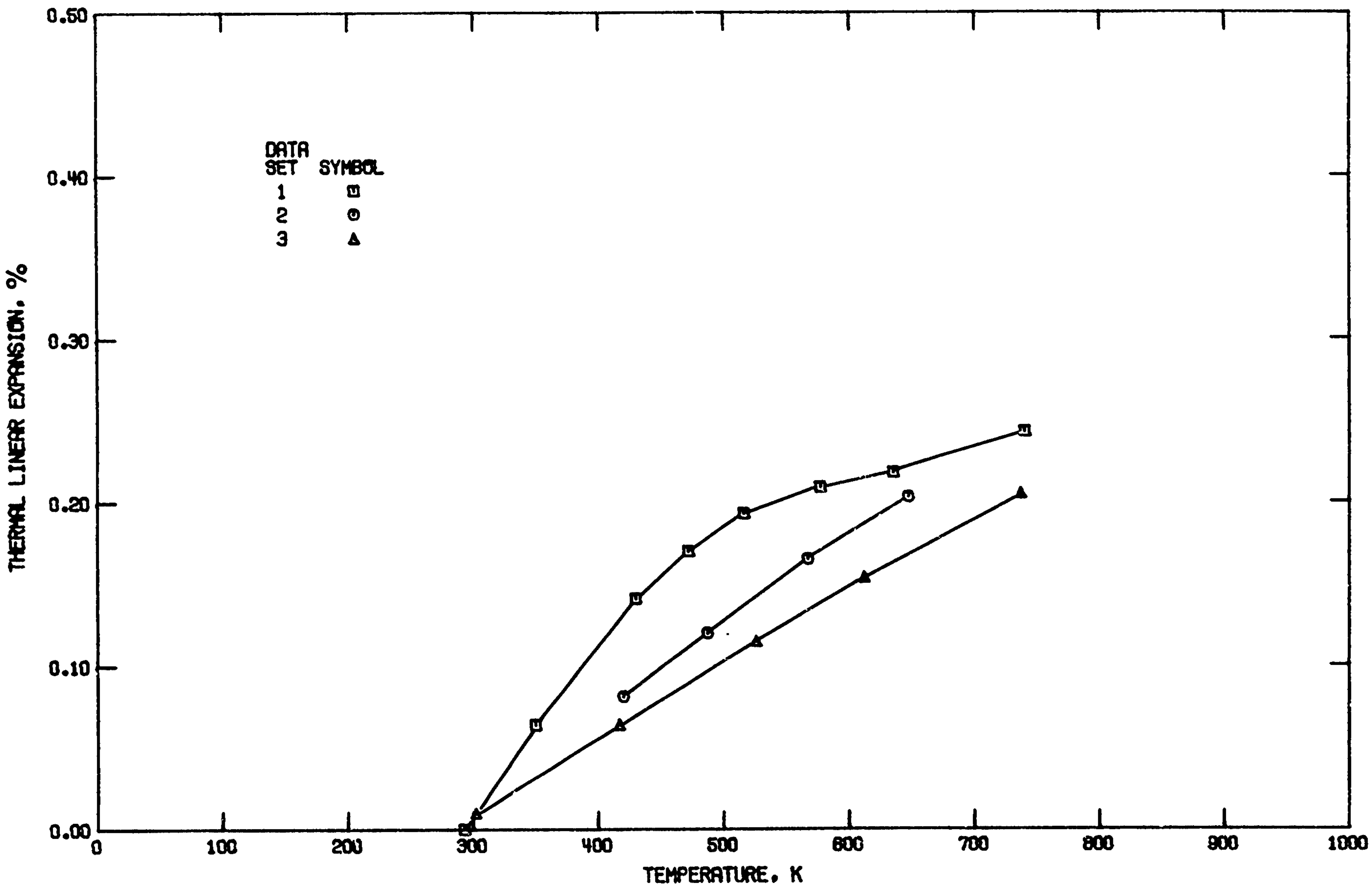

FIGURE 34. THERMAL LINEAR EXPANSION OF TUNGSTEN FIBER. COPPER MATRIX COMPOSITE.

TABLE 24. DATA ON THE ELECTRICAL RESISTIVITY OF TUNGSTEN FIBER, COPPER MATRIX COMPOSITE (FIBER VOLUME DEPENDENCE)

[Fiber Volume, V, % ;Electrical Resistivity, ρ, 10^{-8} Ω m]

Data Set [Ref.]	Vol.	Prop.	Specifications and Remarks	Author(s), Year
	V	ρ	ELECTRICAL RESISTIVITY	
1 [1]	9.67	1.93	Copper Matrix with tungsten wires of 0.1 mm diameter, 30 mm long, were prepared by the method of casting in a vacuum and a hydrogen atmosphere; the specimen have continuous structure.	Rubal'chenko, M. K., Ustinov, L. M., and Zhamnova, V. I., 1972
	9.17	1.91		
	9.10	1.85		
	8.82	1.88		
	9.17	1.83		
	9.17	1.85		
	17.15	2.13		
	17.25	2.14		
	17.25	2.17		
	20.03	2.38		
	20.60	2.33		
	21.90	2.30		
	25.70	2.23		
	26.20	2.14		
	25.70	2.21		
	25.90	2.20		
	28.10	2.31		
	28.40	2.33		
	35.3	2.32		
	36.7	2.25		
	40.0	2.55		
	40.0	2.51		
	42.6	2.49		
	43.8	2.57		
	51.4	2.45		

TABLE 24. DATA ON THE ELECTRICAL RESISTIVITY OF TUNGSTEN FIBER, COPPER MATRIX COMPOSITE (FIBER VOLUME DEPENDENCE) (continued)

Data Set [Ref.]	Vol.	Prop.	Specifications and Remarks	Author(s), Year
	V	ρ	ELECTRICAL RESISTIVITY (cont.)	
2 [1]	17.0 21.0 21.0	2.69 2.60 2.25	Copper matrix with tungsten wires of 0.1 mm diameter, 4 mm long, were prepared by the method of casting in a vacuum and a hydrogen atmosphere, the specimen have discrete structure.	Rubal'chenko, M. K., et al, 1972
3 [1]	20.0 23.0 24.0	2.83 2.61 2.82	Similarly as above, except the specimen have tungsten wires 9 mm in length.	Rubal'chenko, M. K., et al, 1972
4 [1]	18.0 19.0 25.0	2.54 2.80 2.30	Similarly as above except the specimen have tungsten wires 12 mm in length.	Rubal'chenko, M. K., et al, 1972

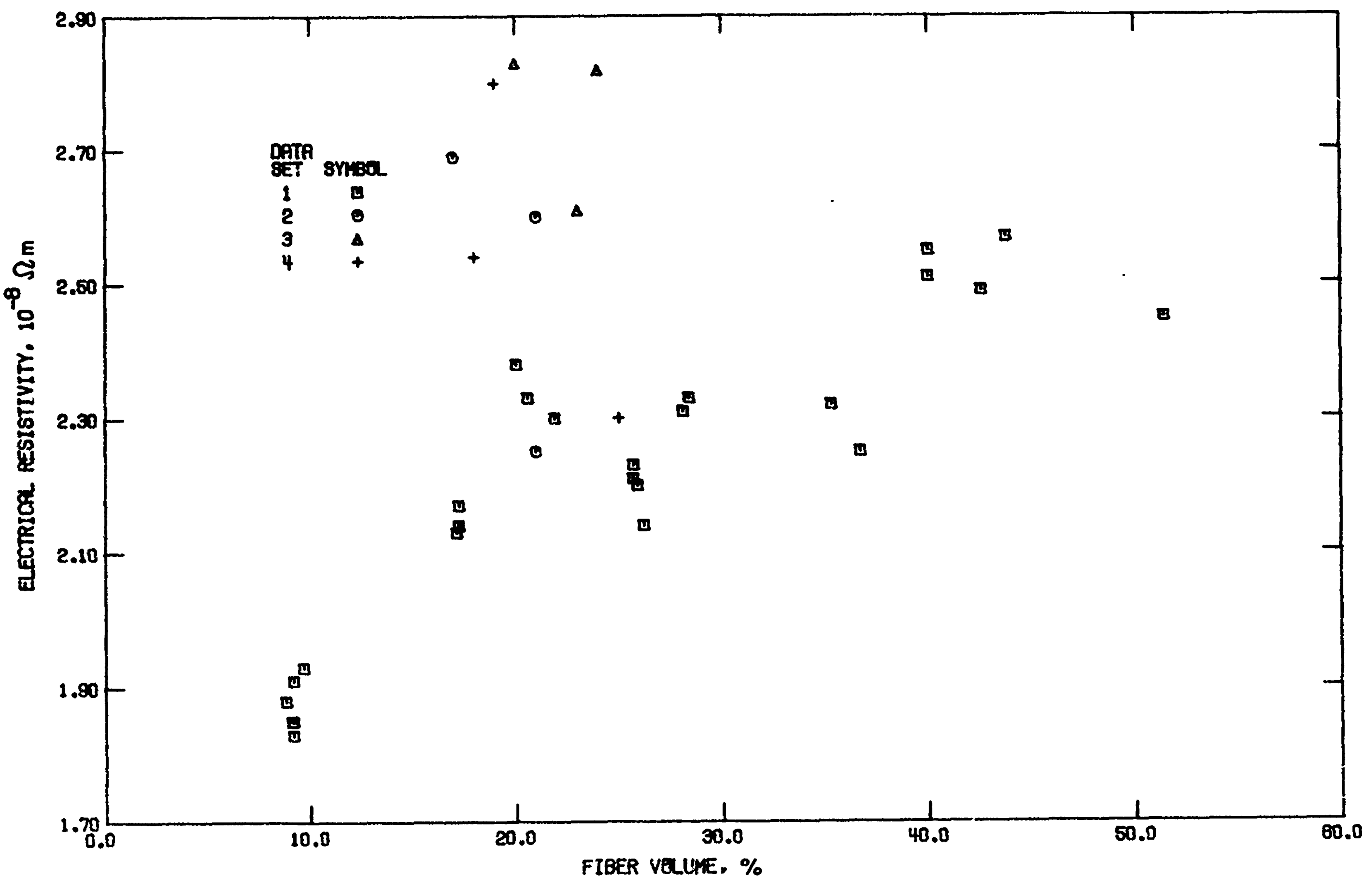

FIGURE 35. ELECTRICAL RESISTIVITY OF TUNGSTEN FIBER, COPPER MATRIX COMPOSITE.

2.4. TUNGSTEN MESH, COPPER MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Salibekov et al. [1] reported thermal expansion data for a composite containing 12 volume percent tungsten net in a copper matrix. This composite expands about 0.52 percent near 1073 K (measurement direction is not reported).

THERMAL CONDUCTIVITY

There are two references [2,3] in which the thermal conductivity of tungsten mesh copper matrix composite is reported. The tungsten mesh content of these specimens varies from 3.7 to 13.4 volume percent [2], and from 3.7 to 12 volume percent [3]. Ref. [3] also reported conditions (pressure, temperature, and time) under which the specimens were prepared. However, some of the data appear to be duplicates (c.f. data sets 1 and 5, 2 and 6, and 3 and 7) as one of the authors is common to both of these references.

ELECTRICAL RESISTIVITY

There are four data sets on the electrical resistivity of copper matrix with tungsten network available from reference [2] as a function of temperature from 100 to 500 K at tungsten volume of 3.7, 7.2, 12 and 23.4%. The measurements were made in the direction parallel to the reinforced networks.

REFERENCES

1. Salibekov, S.E., Portnoi, K.I., and Chubarov, V.M., High Temp., 10(4), 702-6, 1972.

2. Dul'nev, G.N., Zarichnyak, Yu.P., and Machavariani, E.S., High Temp., 11(4), 800-2, 1973.

3. Machavariani, E.S., Avaliani, D.I., and Museliani, V.Sh., Soobshch. Akad. Nauk, Gruz. SSR, 66(2), 377-9, 1972.

TABLE 25. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF TUNGSTEN MESH, COPPER MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %; Thermal Conductivity, λ, W m^{-1} K^{-1}; Electrical Resistivity, ρ, 10^{-8} Ω m]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	293	0.000 *	12 volume % tungsten net; composite obtained by vacuum impregnation of net with liquid copper; specimen heated in argon atmosphere at 3 degrees min^{-1}; accuracy ±5%; dilatometry;measurement direction not reported; data extracted from figure; first heating cycle.	Salibekov, S. E., Portnoi, K. I., and Chubarov, V. M., 1972
	295	0.006 *		
	365	0.105		
	438	0.203		
	511	0.286		
	546	0.327		
	606	0.362		
	699	0.381		
	781	0.387		
	367	0.390		
	930	0.400		
	994	0.403		
	1070	0.410		
2 [1]	302	0.010 *	Similar to the absove except first cooling cycle; zero point correction is 0.14%.	Salibekov, S. E., et al., 1972
	375	0.086		
	435	0.159		
	499	0.219		
	553	0.277		
	587	0.302		
	657	0.346		
	705	0.372		
	778	0.407		
	841	0.448		
	927	0.483		
	1003	0.521		
	1057	0.543		

TABLE 25. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF TUNGSTEN MESH, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
3 [1]	327	0.046	Similar to the above except second heating measurements; zero point correction is 0.138%.	Salibekov, S. E., et al., 1972
	394	0.141		
	464	0.246		
	517	0.309		
	556	0.360		
	594	0.389		
	651	0.408		
	708	0.421		
	775	0.433		
	854	0.440		
	908	0.455		
	975	0.468		
	1032	0.490		
	1070	0.503		
4 [1]	305	0.012 *	Similar to the above specimen except second cooling cycle; zero point correction is 0.168%.	Salibekov, S. E., et al., 1972
	372	0.082 *		
	426	0.136		
	514	0.219		
	584	0.282		
	619	0.305		
	641	0.324		
	673	0.343		
	743	0.378		
	826	0.409		
	873	0.431		
	914	0.451		
	959	0.473		
	1006	0.498		
	1041	0.514		
	1064	0.527		

TABLE 25. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF TUNGSTEN MESH, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.		Specifications and Remarks	Author(s), Year
	T	λ		THERMAL CONDUCTIVITY	
1 [2]	100	474.	*	Tungsten wire mesh net-work in a copper matrix, made by diffusion welding in vacuo; volume content of tungsten 3.7%; heat flow direction parallel to mesh; values from table.	Dul'nev, G. N., Zarichnyak, Yu. P., and Machavariani, E. S., 1973
	150	426.	*		
	200	407.	*		
	300	396.	*		
	400	387.	*		
	500	383.	*		
2 [2]	100	457.	*	Similar to the above except tungsten volume content 7.2%.	Dul'nev, G. N., et al., 1973
	150	414.	*		
	200	395.	*		
	300	380.	*		
	400	370.	*		
	500	362.	*		
3 [2]	100	440.	*	Similar to the above except tungsten content 12%.	Dul'nev, G. N., et al., 1973
	150	398.	*		
	200	384.	*		
	300	365.	*		
	400	356.	*		
	500	350.	*		
4 [2]	100	385.	*	Similar to the above except tungsten content 13.4%.	Dul'nev, G. N., et al., 1973
	150	347.	*		
	200	330.	*		
	300	313.	*		
	400	304.	*		
	500	300.	*		

TABLE 25. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF TUNGSTEN MESH, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
5 [3]	100	449.	Composite material made of alternating layers of copper and tungsten, prepared by the diffusion welding of copper foils and tungsten wire gauzes; welded under a pressure of 26 bar for 15 min. at 1193K; tungsten content 3.7% by volume; diameter of tungsten wire 0.03 mm; smoothed values from graph.	Machavariani, E. S., Avaliani, D. I., and Museliani, V. Sh., 1972
	150	413.		
	200	392.		
	250	385.		
	300	378.		
	400	369.		
	500	364.		
6 [3]	100	431.	Similar to the above except tungsten content 7.2% by volume.	Machavariani, E. S., et al., 1972
	150	391.		
	200	372.		
	250	361.		
	300	355.		
	400	346.		
	500	341.		
7 [3]	100	423.	Similar to the above except tungsten content 12.0% by volume and diameter of tungsten wire 0.04 mm.	Machavariani, E. S., et al., 1972
	150	381.		
	200	358.		
	250	346.		
	300	339.		
	400	328.		
	500	323.		
8 [3]	100	454.	Similar to the above except welded under a pressure of 30 bar for 60 minutes at 1193 K; tungsten content	Machavariani, E. S., et al., 1972
	150	418.		
	200	399.		

TABLE 25. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF TUNGSTEN MESH, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
8 (cont.) [3]	250	389.	3.7% by volume; diameter of tungsten wire 0.03 mm.	
	300	382.		
	400	372.		
	500	368.		
9 [3]	100	436.	Similar to the above except tungsten content 7.2% by volume.	Machavariani, E. S., et al., 1972
	150	398.		
	200	377.		
	250	367.		
	300	360.		
	400	350.		
	500	344.		
10 [3]	100	415.	Similar to the above except tungsten content 12.0% by volume and diameter of tungsten wire 0.04 mm.	Machavariani, E. S., et al., 1972
	150	376.		
	200	354.		
	250	344.		
	300	335.		
	400	324.		
	500	316.		
	T	ρ	ELECTRICAL RESISTIVITY	
1 [2]	100	0.35	Copper-tungsten network made by diffusion welding in vacuo; the electrical resistivity was measured by a dc potentiometric method; the measurements were made in the direction parallel to the reinforced networks; 3.7 volume % fiber content.	Dul'nev, G. N., Zarichnyak, Yu. P., and Machavariani, E. S., 1973
	150	0.72		
	200	1.08		
	300	1.86		
	400	2.61		
	500	3.45		

TABLE 25. DATA ON THE THERMOPHYSICAL PROPERTIES AND ELECTRICAL RESISTIVITY OF TUNGSTEN MESH, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	ρ	ELECTRICAL RESISTIVITY (cont.)	
2 [2]	100	0.36	Similarly as above except fiber volume is 7.2%.	Dul'nev, G. N., et al., 1973
	150	0.75		
	200	1.11		
	300	1.92		
	400	2.70		
	500	3.57		
3 [2]	100	0.39	Similarly as above except fiber volume is 12%.	Dul'nev, G. N., et al.,1973
	150	0.77		
	200	1.15		
	300	2.02		
	400	2.90		
	500	3.75		
4 [2]	100	0.48	Similarly as above except fiber volume is 23.4%.	Dul'nev, G. N., et al., 1973
	150	0.98		
	200	1.37		
	300	2.50		
	400	3.77		
	500	4.98		

*Not shown in figure.

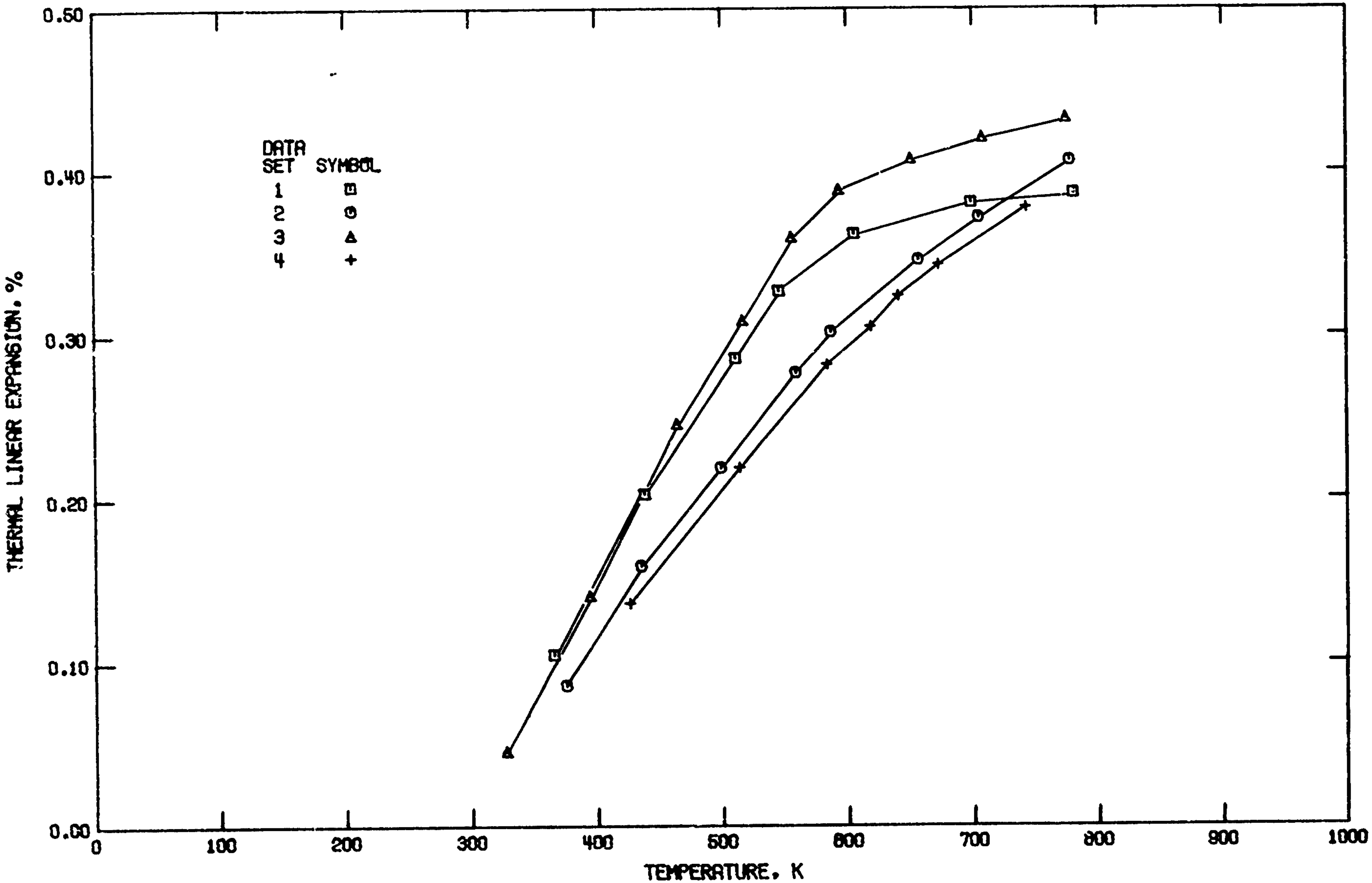

FIGURE 36. THERMAL LINEAR EXPANSION OF TUNGSTEN MESH. COPPER MATRIX COMPOSITE.

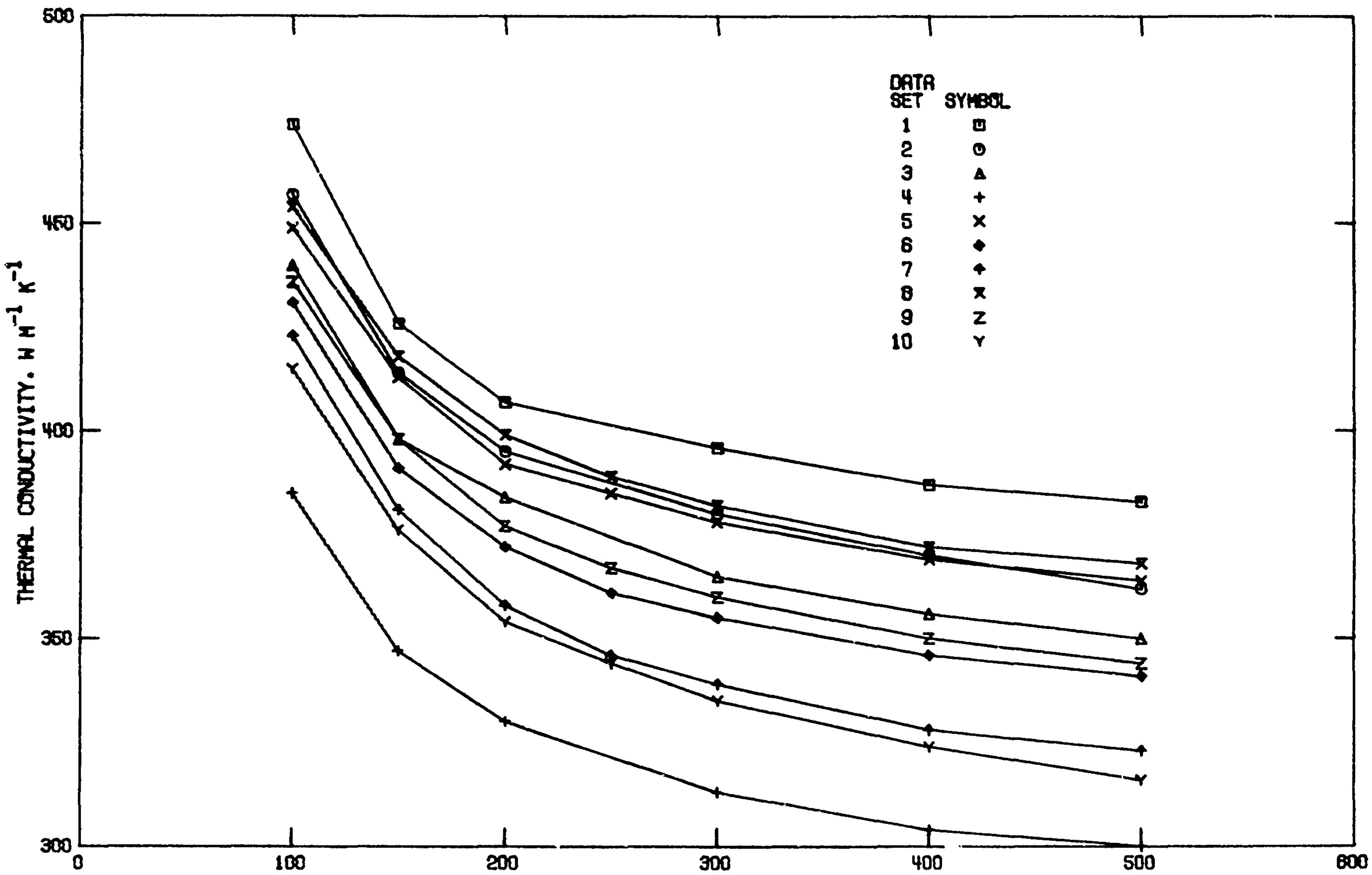

FIGURE 37. THERMAL CONDUCTIVITY OF TUNGSTEN MESH, COPPER MATRIX COMPOSITE.

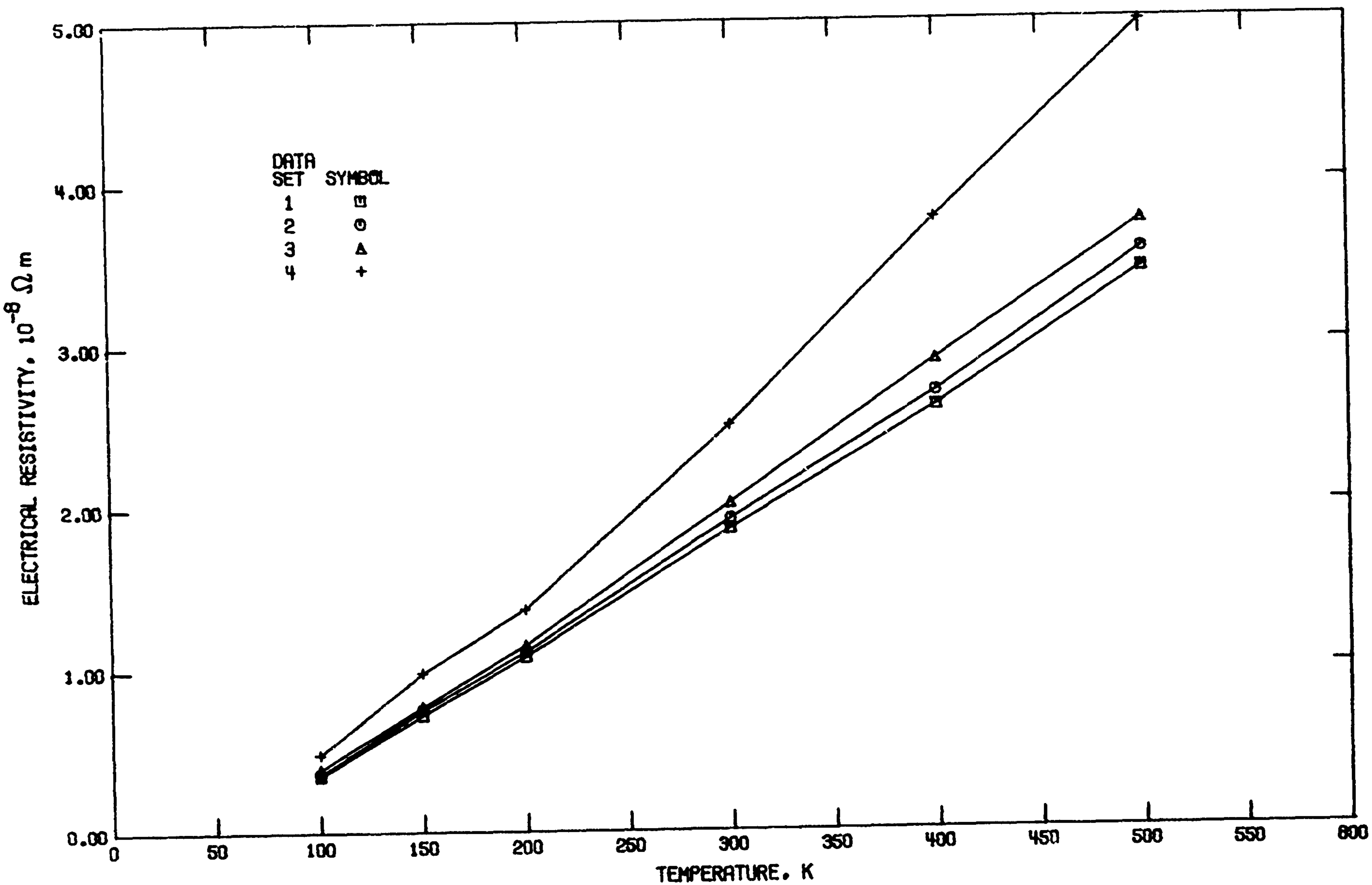

FIGURE 38. ELECTRICAL RESISTIVITY OF TUNGSTEN MESH, COPPER MATRIX COMPOSITE.

2.5. POLYVINYL CHLORIDE FIBER, COPPER MATRIX COMPOSITE

ELECTRICAL RESISTIVITY

Seven data sets on the electrical resistivity of composites containing polyvinyl chloride fibers in a copper matrix have been reported [1]. The data show that at low copper volume loading, the composite resistivity is essentially that of the insulating polymer($\sim 10^{12}$ Ω m). A dramatic fall of resistivity in the neighborhood of 5 volume percent copper loading occurs due to the formation of a segregated network. The resistivity of the annealed samples with increased metal loadings always shows higher values than that of the samples before annealing, probably due to the elimination of all free ions during prolonged annealing or due to the metal particles in the bulk of the material leading to a more stable configuration. The increase of resistivity with the increase of temperature is almost logarithmic which may be due to the different coefficients of thermal expansion of the polymer and the metal. The internal stresses localized around the metal particles decrease with increasing temperature as the thermal expansion coefficient of the metal is lower in comparison with that of the polymer. This leads to a fall in contact pressure between the metal particles, which results in an increase of resistivity with increasing temperature.

REFERENCE

1. Bhattacharya, S.K., Basu, S., De, S.K., Pal, A., and Chowdhury, S., J. Appl. Phys., 49(5), 3001-3, 1978.

TABLE 26. DATA ON THE ELECTRICAL RESISTIVITY OF POLYVINYL CHLORIDE FIBER, COPPER MATRIX COMPOSITE

[Electrical Resistivity, ρ, 10^{-8} Ω m]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	ρ	ELECTRICAL RESISTIVITY	
1 [1]	272	0.0182	Weighed amounts of PVC from sieved out fraction 100-200 mesh size (average particle size 112 μm) and electrolytic copper powder (average particle size 6.2 μ) were thoroughly mixed by tumbling at room temperature and compacted in a steel cylindrical die at 7000 psi; the temperature was raised to 130°C and maintained constant for 15 minutes. The die assembly was then cooled and sample was removed from the die at 50-60°C; samples were taken in the form of rectangular blocks of dimensions 1.5 x 1 x 0.7 cm; prior to the measurements, the samples were kept under vacuum for 48 hours to minimize and effect due to moisture, each sample was then placed in a vacuum chamber flushed with inert gas by alternating pumping and introduction of the gas into the chamber, this process was carried out several times to ensure complete removal of air, finally the chamber was filled with argon at 700 Tor, 5 volume % Cu annealed composites.	Bhattacharyya, S. K., Basu, S., De, S. K., Pal, A. K., and Chowdhury, S., 1978
	277	0.0185		
	283	0.0190		
	290	0.0195		
	295	0.0199		
	300	0.0202		
	307	0.0208		

TABLE 26. DATA ON THE ELECTRICAL RESISTIVITY OF POLYVINYL CHLORIDE FIBER, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	ρ	ELECTRICAL RESISTIVITY (cont.)	
2 [1]	272	0.0137	Similarly as above, 7.5 volume % of Cu, annealed composite.	Bhattacharyya, S. K., et al., 1978
	275	0.0139		
	279	0.0143		
	281	0.0147		
	288	0.0152		
	293	0.0155		
	297	0.0158		
	302	0.0162		
	306	0.0167		
3 [1]	275	0.0110	Similarly as above, 10 volume % of Cu, annealed composite.	Bhattacharyya, S. K., et al., 1978
	280	0.0111		
	287	0.0114		
	292	0.0123		
	297	0.0126		
	303	0.0129		
	307	0.0131		
4 [1]	273	0.00764	Similarly as above, 12.5 volume % of Cu, annealed composite.	Bhattacharyya, S. K. et al., 1978
	276	0.00757		
	280	0.00750		
	286	0.00791		
	295	0.00836		
	302	0.00869		
	307	0.00897		
5 [1]	277	0.00465	Similarly as above, 15 volume % of Cu, annealed composite.	Bhattacharyya, S. K. et al., 1978
	282	0.00469		
	288	0.00478		

TABLE 26. DATA ON THE ELECTRICAL RESISTIVITY OF POLYVINYL CHLORIDE FIBER, COPPER MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	ρ	ELECTRICAL RESISTIVITY (cont.)	
5 (cont.) [1]	295	0.00520		
	302	0.00598		
	312	0.00675		

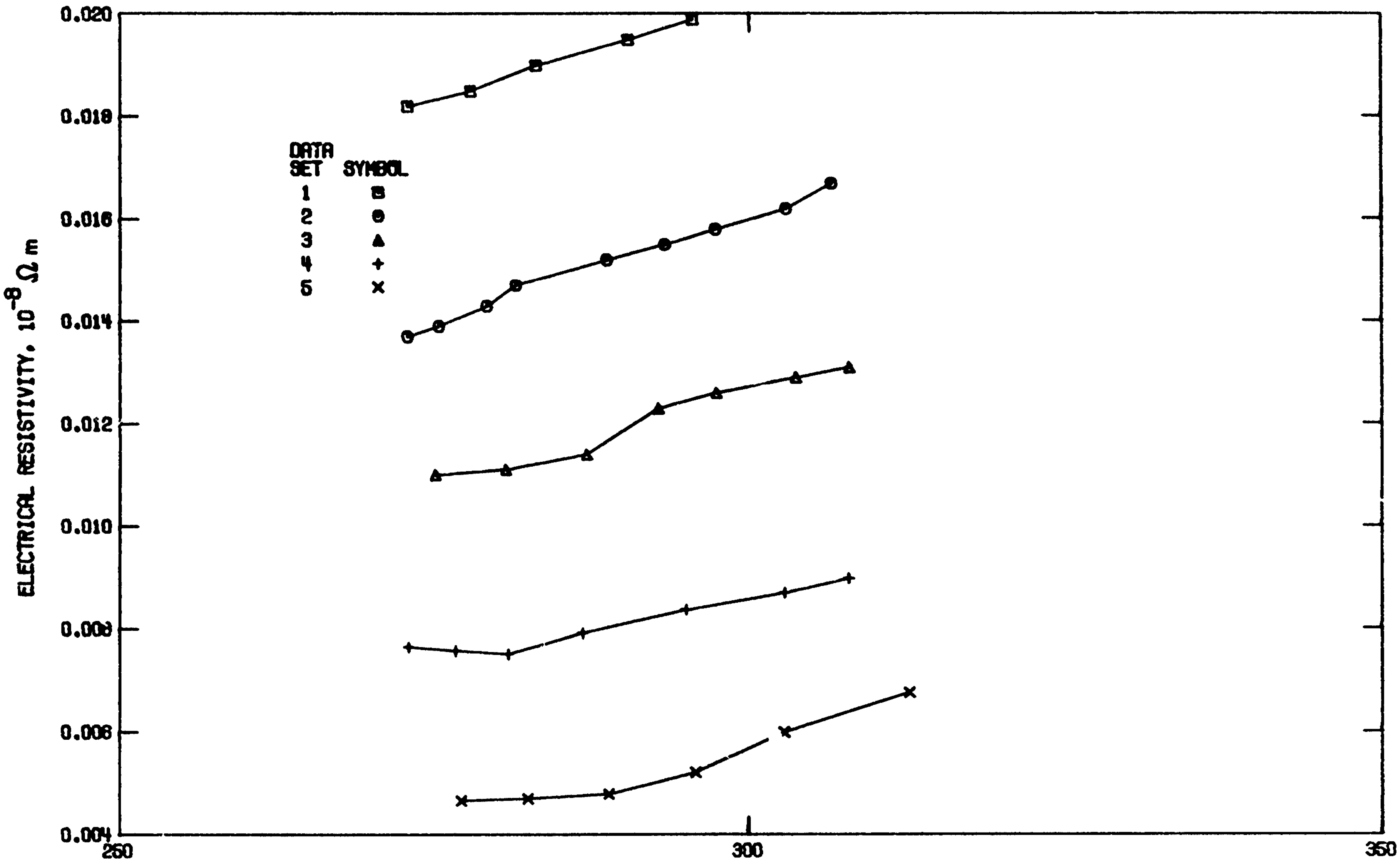

FIGURE 39. ELECTRICAL RESISTIVITY OF POLYVINYL CHLORIDE FIBER.
COPPER MATRIX COMPOSITE.

TABLE 27. DATA ON THE ELECTRICAL RESISTIVITY OF POLYVINYL CHLORIDE FIBER, COPPER MATRIX COMPOSITE (FIBER VOLUME DEPENDENCE)

[Fiber Volume, V, % ;Electrical Resistivity, ρ, 10^{-8} Ω m]

Data Set [Ref.]	Vol.	Prop.	Specifications and Remarks	Author(s), Year
	V	ρ	ELECTRICAL RESISTIVITY	
1 [1]	2.00	4.22E+11	Weighed amounts of PVC from sieved out fraction 100-200 mesh size (average particle size 112 μm) and electrolytic copper powder (average particle size 6.2 μ) were thoroughly mixed by tumbling at room temperature and compacted in a steel cylindrical die at 7000 psi; the temperature was raised to 130°C and maintained constant for 15 minutes. The die assembly was then cooled and sample was removed from the die at 50-60°C; samples were taken in the form of rectangular blocks of dimensions 1.5 x 1 x 0.7 cm; prior to the measurements, the samples were kept under vacuum for 48 hours to minimize and effect due to moisture, each sample was then placed in a vacuum chamber flushed with inert gas by alternating pumping and introduction of the gas into the chamber, this process was carried out several times to ensure complete removal of air, finally the chamber was filled with argon at 700 Torr.	Bhattacharyya, S. K., Basu, S., De, S. K., Pal, A. K., and Chowdhury, S., 1978
	3.00	3.30E+11		
	5.00	2.81E+11		
	7.50	3.38E-02		
	10.0	3.72E-03		
	12.5	2.26E-03		
	15.0	1.55E-03		

TABLE 27. DATA ON THE ELECTRICAL RESISTIVITY OF POLYVINYL CHLORIDE FIBER, COPPER MATRIX COMPOSITE (FIBER VOLUME DEPENDENCE) (continued)

Data Set [Ref.]	V. I.	Prop.	Specifications and Remarks	Author(s), Year
	V	ρ	ELECTRICAL RESISTIVITY (cont.)	
2 [1]	2.00	2.30E+11	Same as above except the composites have been annealed at 50°C for 10 days.	Bhattacharyya, S. K. et al, 1978
	3.00	1.79E+11		
	5.00	2.37E-02		
	7.50	1.63E-02		
	10.0	1.43E-02		
	12.5	8.65E-03		
	15.0	5.26E-03		

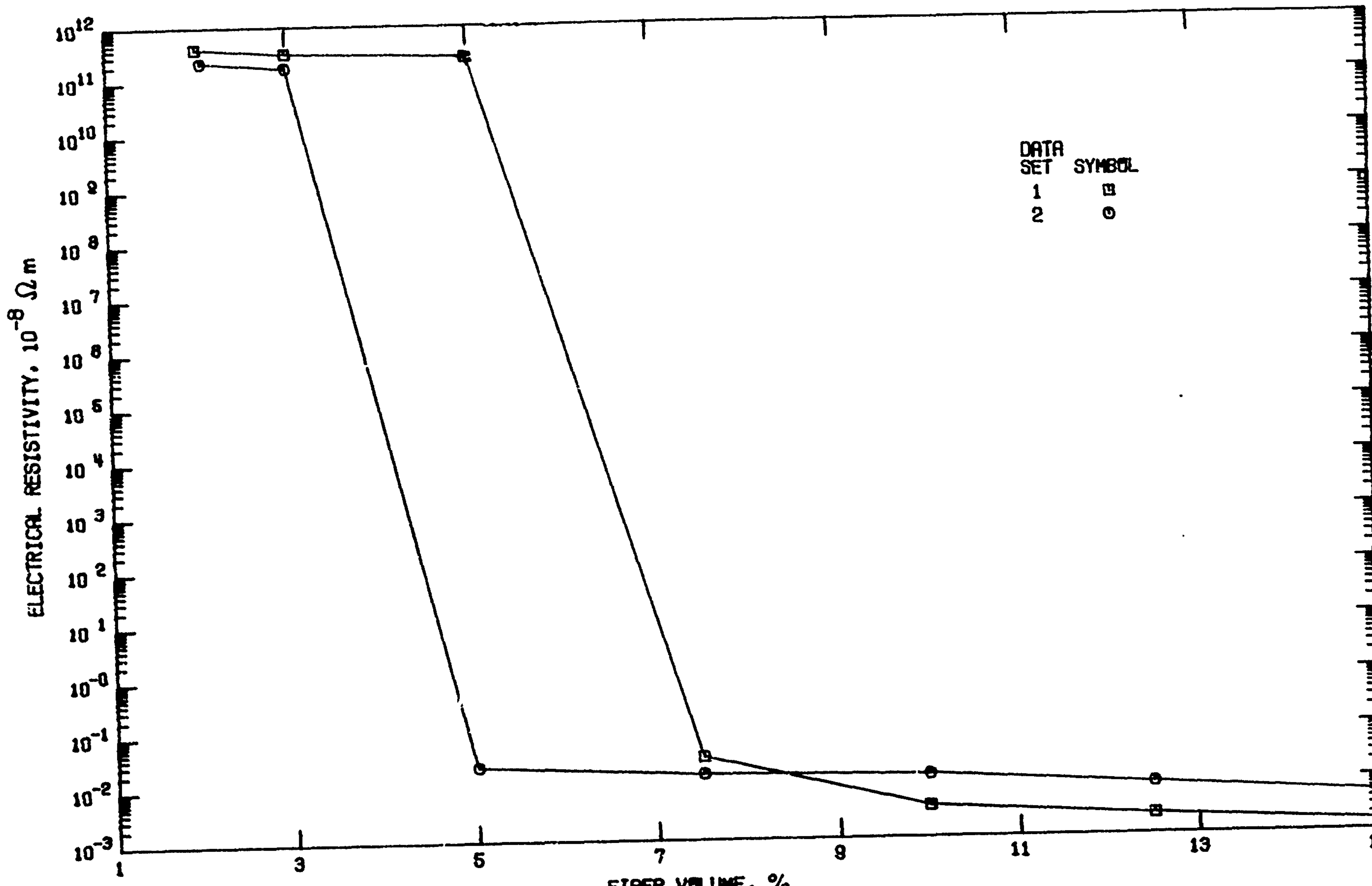

FIGURE 40. ELECTRICAL RESISTIVITY OF POLYVINYL CHLORIDE FIBER, COPPER MATRIX COMPOSITE.

CHAPTER 3

LEAD AND LEAD ALLOY MATRIX COMPOSITES

3.1. 'E' GLASS FIBER, LEAD MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Whitehurst et al.[1] and Lockwood [2] reported a value of about 0.138 for the percent thermal expansion at 564 K for a composite containing 20 volume percent parallel oriented 'E' glass fibers in a lead matrix.

REFERENCES

1. Whitehurst, H.B., Michener, J.M., and Lockwood, P.A., Proc. 6th Sagamore Army Mater. Res. Conf., 248-76, 1960. [AD-233 158]
2. Lockwood, P.A., Owens-Corning Fiberglas Corp. Rept., 164 pp., 1960. [AD-274 530]

TABLE 28. DATA ON THE THERMAL LINEAR EXPANSION OF 'E' GLASS FIBER, LEAD MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	308	0.001	'E' glass fibers 20 volume %, 0.0006 inch in diameter and parallel oriented; lead matrix composites have been heated several times or normatized at their service temperature before experiments; average of heating and cooling; measurement direction not reported; data extracted from figure.	Whitehurst, H. B., Michener, J. M., and Lockwood, P. A., 1966
	342	0.015		
	365	0.030		
	394	0.043		
	419	0.059 *		
	441	0.073		
	466	0.087		
	475	0.092		
	508	0.108		
	531	0.120		
	548	0.124		
	564	0.131		
2 [2]	293	0.000	0.0006 inch diameter 20 volume % 'E' glass fibers; parallel orientation; vacuum injection casting; average of heating and cooling cycle; measurement direction not reported; data extracted from figure.	Lockwood, P. A., 1960
	311	0.007		
	365	0.030		
	423	0.060		
	477	0.090		
	532	0.120		
	571	0.138		

*Not shown in figure.

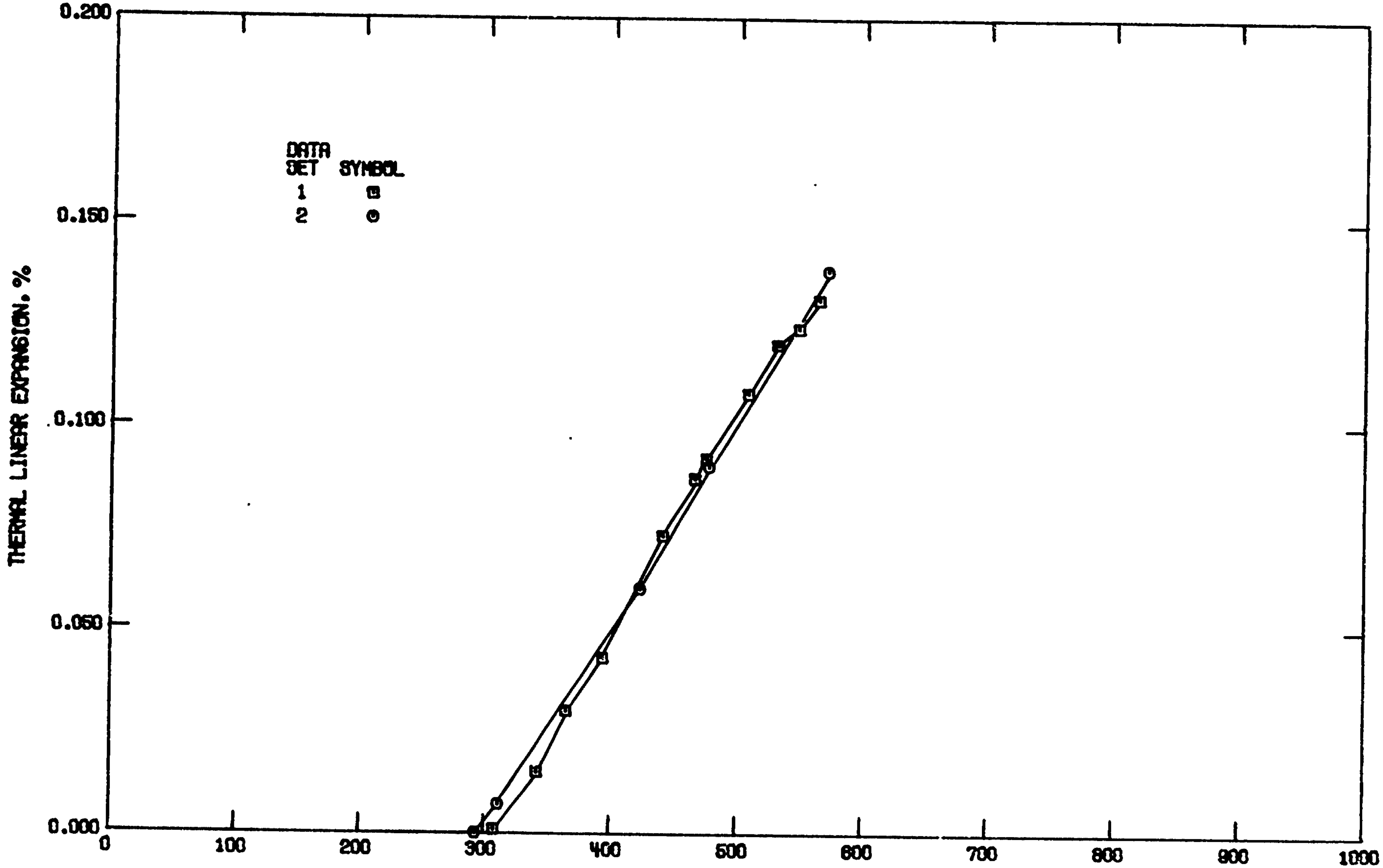

FIGURE 41. THERMAL LINEAR EXPANSION OF E GLASS FIBER. LEAD MATRIX COMPOSITE.

CHAPTER 4

MAGNESIUM AND MAGNESIUM ALLOY MATRIX COMPOSITES

4.1. GRAPHITE FIBER, MAGNESIUM MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Pincheiro et al. [1] reported thermal expansion data for a composite containing 35 volume percent "Thornel 50" graphite fibers in a magnesium matrix. This composite expands about 0.041 percent at 470 K. Armstrong and Ellison [2] reported a value of $0.9 \times 10^{-6}\,°F^{-1}$ between 0° and −250°F for the mean coefficient of thermal expansion of a composite containing 38.5 volume percent GY 70 graphite fibers.

THERMAL CONDUCTIVITY

There is one reference [1] in which the thermal conductivity of graphite fiber (Thornel 50) magnesium matrix composite is reported. The data cover room temperature and below (to ~3 K).

REFERENCES

1. Pincheiro, M. de F.F., Radcliffe, D.J., and Rosenberg, H.M., Oxford Univ., Clarendon Lab. Rept., 1, 3–13, 1978. [AD-A061 105]
2. Armstrong, H.H. and Ellison, A.M., U.S. Air Force Rept. AFML-TR-79-4007, 213 pp., 1979.

TABLE 29. DATA ON THE THERMOPHYSICAL PROPERTIES OF GRAPHITE FIBER, MAGNESIUM MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %; Thermal Conductivity, λ, W m^{-1} K^{-1}]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	28	-0.005	35 volume % Thornel 50 graphite fibers in a magnesium metal matrix; composite made by melting the magnesium around the fibers with some titanium powder; measurements in the direction parallel to the fibers using a "standard capacitative method"; data extracted from figure.	Fincheiro, M de F. F., Radcliff, D. J., and Rosenberg, H. M., 1978
	37	-0.005		
	42	-0.006		
	46	-0.006		
	53	-0.007		
	64	-0.008		
	67	-0.008		
	77	-0.007		
	93	-0.007		
	103	-0.008		
	118	-0.008		
	134	-0.007		
	147	-0.009		
	155	-0.008		
	164	-0.008		
	186	-0.006		
	203	-0.006		
	230	-0.006		
	257	-0.004		
	264	-0.002		
	304	0.005		
	329	0.011		
	357	0.021		
	389	0.025		
	414	0.031		
	447	0.037		
	470	0.041		

TABLE 29. DATA ON THE THERMOPHYSICAL PROPERTIES OF GRAPHITE FIBER, MAGNESIUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY	
1 [1]	3.23	45.8	35 volume % Thornel 50 carbon fiber in magnesium matrix; made by melting magnesium around the fibers with some titanium powder present.	Pincheiro, M. de F. F., Radcliffe, D. J., and Rosenberg, H. M., 1978
	3.91	53.1		
	4.29	58.8		
	4.45	61.5		
	4.97	68.7		
	9.80	129.		
	9.98	125.		
	11.1	136.		
	13.3	162.		
	13.8	168.		
	14.0	165.		
	15.4	177.		
	15.6	186.		
	16.2	179.		
	18.1	193.		
	18.3	200.		
	18.8	202.		
	19.5	204.		
	20.6	208.		
	44.1	159.		
	55.0	124.		
	63.1	106.		
	70.4	96.6		
	77.2	86.5		
	80.8	84.9		
	84.6	82.6		
	102.	79.6		
	121.	81.9		
	195.	99.3		
	274.	116.		
	289.	116.		

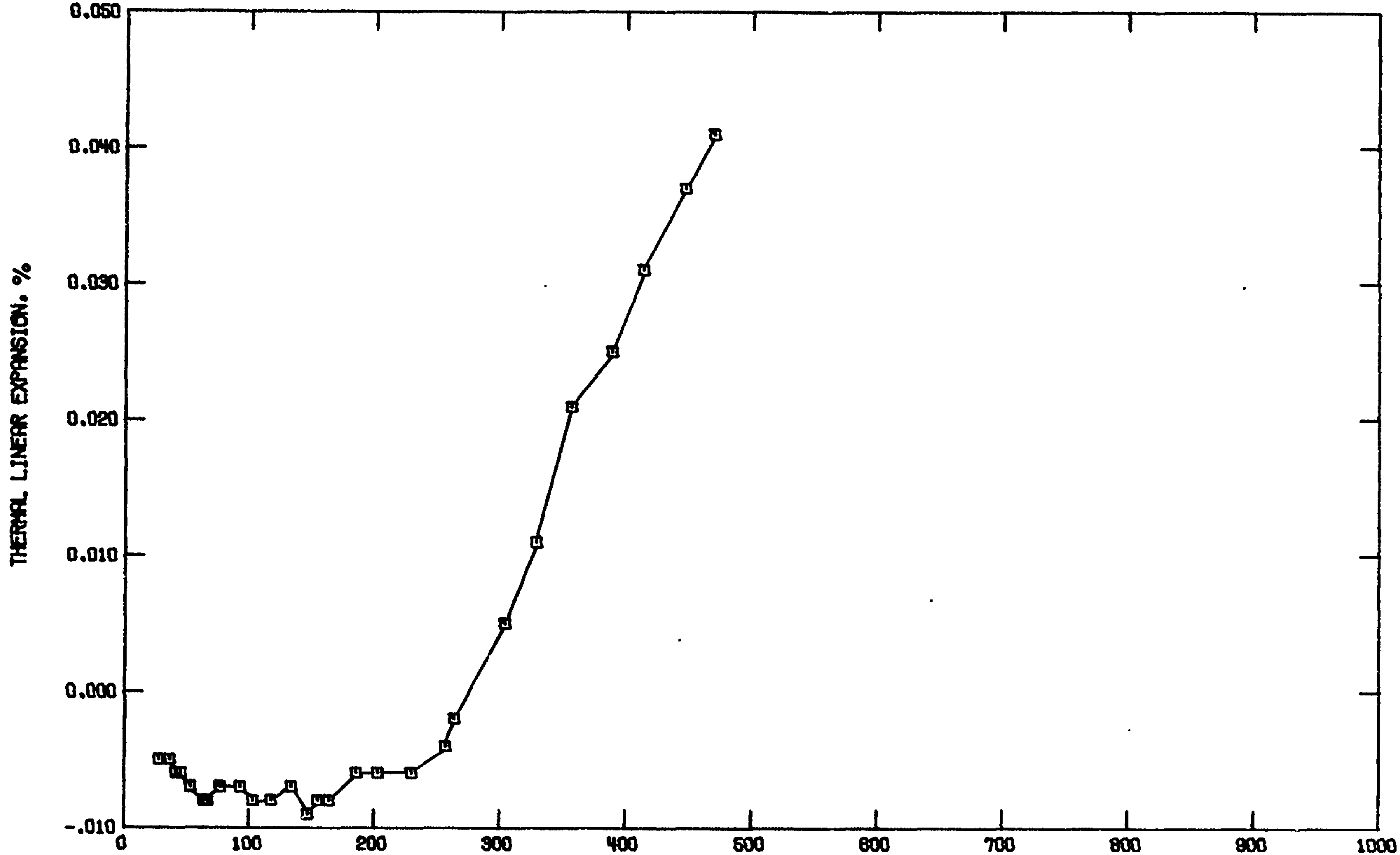

FIGURE 42. THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, MAGNESIUM MATRIX COMPOSITE.

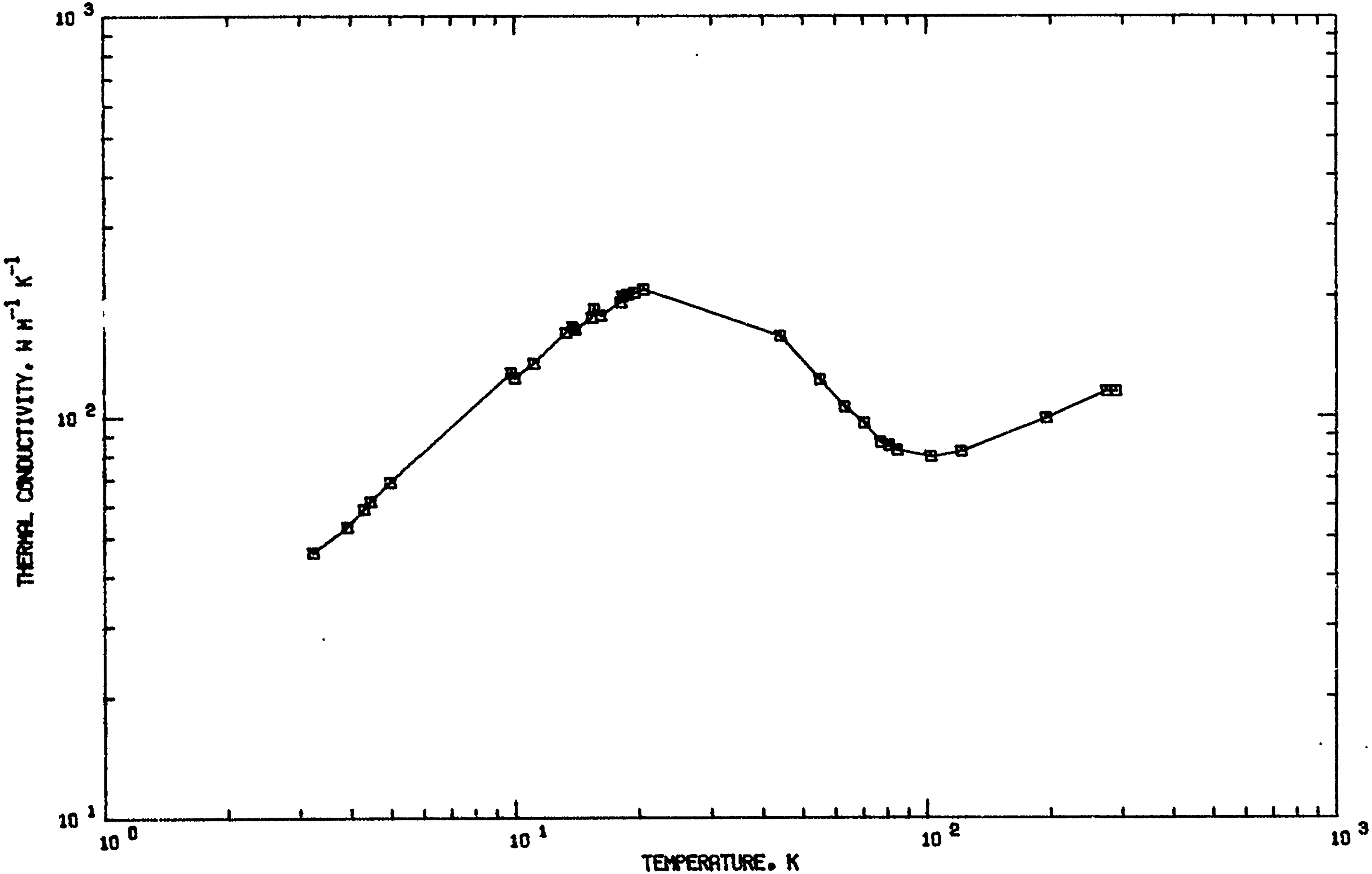

FIGURE 43. THERMAL CONDUCTIVITY OF GRAPHITE FIBER, MAGNESIUM MATRIX COMPOSITE.

CHAPTER 5

NICKEL AND NICKEL ALLOY MATRIX COMPOSITES

5.1. CARBON FIBER, NICKEL MATRIX COMPOSITE

THERMAL CONDUCTIVITY

There is one reference [1] in which the thermal conductivity of carbon fiber nickel matrix composite is reported. The data are for specimens having 35 to 55 volume percent fiber content, and for heat flow both in the parallel and the perpendicular (to the fiber) directions. However, the temperature at which these data were obtained was not given, and it was assumed to be 293 K. No other information on the composites was reported.

REFERENCE

1. Fitzer, E., Fritz, W., Geigl, K.H., and Vohmann, W., 5th European Conf. on Thermophys. Prop. of Solids at High Temp., 19 pp., 1976.

TABLE 30. DATA ON THE THERMAL CONDUCTIVITY OF CARBON FIBER, NICKEL MATRIX COMPOSITE(FIBER VOLUME DEPENDENCE)

[Fiber Volume, V, % ;Thermal Conductivity, λ, W m^{-1} K^{-1}]

Data Set [Ref.]	Vol.	Prop.	Specifications and Remarks	Author(s), Year
	V	λ	THERMAL CONDUCTIVITY	
1 [1]	35.	38.	Heat flow parallel to fiber; room temperature assumed; value from graph.	Fitzer, E., Fritz, W., Geigl, K. H., and Vohmann, W., 1976
	40.	37.		
	45.	34.		
	50.	32.		
	55.	31.		
2 [1]	40.	13.5	Heat flow perpendicular to fiber; room temperature assumed.	Fitzer, E., et al., 1976
	50.	13.0		

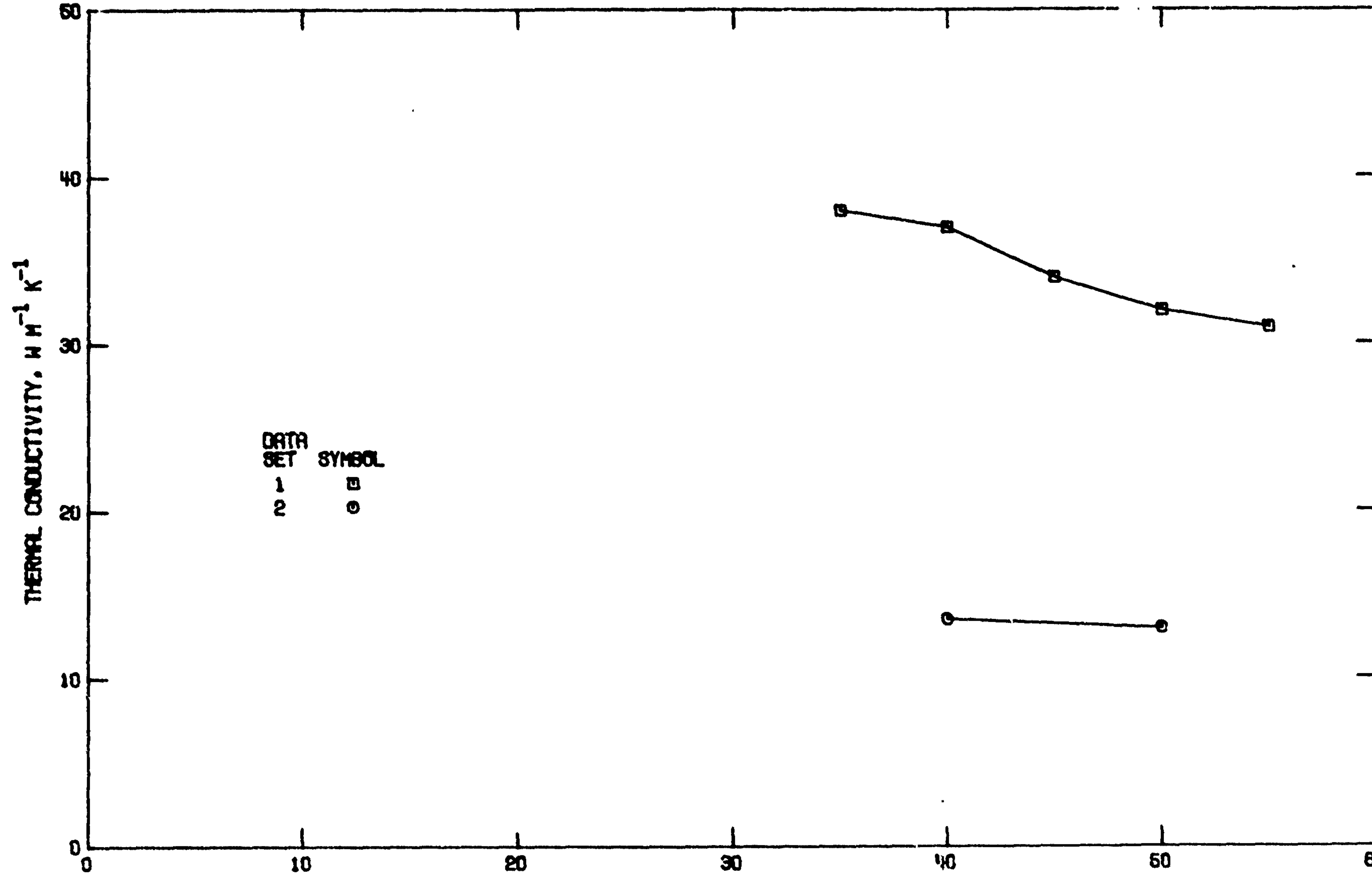

FIGURE 44. THERMAL CONDUCTIVITY OF CARBON FIBER, NICKEL MATRIX COMPOSITE.

5.2. GRAPHITE FIBER, NICKEL MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

There are 28 data sets available for the thermal expansion of this composite as a result of the studies of Volk et al. [1,2], Niesz [3], and Salibekov [4]. The content of graphite fibers ranged from 25 to 50 volume percent. An extensive study of Volk et al. [1,2] yielded the data obtained during numerous thermal cycles (including 100, 500, and 1000 cycles). However, their latter measurements [2] which were repeated principally for increased accuracy and to clarify the cyclic behavior which they obtained earlier [1] could not adequately explain the different longitudinal expansion behavior they obtained in their two studies. All of these investigators [1-4] observed a hysteresis effect in the thermal expansion during various thermal cycles. This was explained as due to the stresses generated in the composite.

REFERENCES

1. Volk, H.F., Nara, H.R., and Hanley, D.P., U.S. Air Force Rept., AFML-TR-66-310-Pt. 4-Vol. I, 99 pp., 1969.
2. Volk, H.F., Nara, H.R., and Hanley, D.P., U.S. Air Force Rept., AFML-TR-66-310-Pt. 5-Vol. I, 144 pp., 1971. [AD-881 488]
3. Niesz, D.E., Battelle Memorial Inst. Rep., 94 pp., 1968. [AD-836 764]
4. Salibekov, S.E., Portnoi, K.I., and Chubarov, V.M., High Temp., 10(4), 702-6, 1972.

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	287	-0.005	Electrodeposition of nickel on unidirectional "Thornel" graphite fibers (46 volume %); hot-pressed at about 1050°C and 2000-3500 psi pressure for one hour to compress the nickel coated yarn into dense composites; specimen dimensions 3 x 1/2 x 1/16 inch; specimen were heated in a graphite tube furnace in a helium atmosphere to prevent oxidation; longitudinal expansion; first heating cycle; zero point is correction -0.018%; data extracted from figure.	Volk, H. F., Nara, H. R., and Hanley, D. P., 1969
	371	0.048		
	472	0.114		
	572	0.180		
	671	0.232 *		
	771	0.285		
	870	0.331		
	970	0.370		
	1069	0.380		
	1172	0.407		
	1272	0.466		
	1306	0.513		
2 [1]	286	0.000	Similar to the above; longitudinal expansion first cooling cycle; zero point correction is -0.013%.	Volk, H. F., et al., 1969
	371	-0.014 *		
	472	-0.016		
	572	0.016		
	673	0.042 *		
	769	0.101		
	870	0.160		
	970	0.240		
	1069	0.326		
	1172	0.432		
	1272	0.519 *		
	1304	0.518		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
3 [1]	286	-0.062 *	Similar to the above; longitudinal expansion second heating cycle; zero point correction is -0.082%.	Volk, H. F., et al., 1969
	371	0.207		
	473	0.536		
	572	0.899		
	671	1.376 *		
	770	1.476		
	868	1.522		
	971	1.534		
	1070	1.593 *		
	1170	1.740		
	1272	2.082		
	1373	2.472 *		
	1395	2.580		
4 [1]	301	0.006 *	Similar to the above; longitudinal expansion second cooling cycle; zero point correction is -1.35%.	Volk, H. F., et al., 1969
	375	0.005		
	472	0.003		
	573	0.069 *		
	671	0.351		
	771	0.552 *		
	869	0.699		
	970	0.866 *		
	1071	1.013		
	1167	1.147 *		
	1270	1.260		
	1373	1.319 *		
	1395	1.312		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
5 [1]	300	0.012 *a	Similar to the above; longitudinal expansion; the data taken during fourth and fifth heating cycles are reported as a band of values; values with suffix "a" are the lower end and with suffix "b" are the higher end of the band at that temperature; data extracted from figure; -1.35% zero point correction.	Volk, H. F., et al., 1969
	300	0.013 *b		
	376	0.227 *a		
	376	0.281 *b		
	474	0.509 *a		
	474	0.631 *b		
	573	0.791 *a		
	573	0.939 *b		
	669	0.992 *a		
	669	1.174 *b		
	772	1.159 *a		
	772	1.321 *b		
	869	1.245 *a		
	869	1.407 *b		
	970	1.284 *a		
	970	1.453 *b		
	1071	1.330 *a		
	1071	1.499 *b		
	1168	1.403 *a		
	1168	1.538 *b		
	1271	1.436 *a		
	1271	1.671 *b		
	1328	1.562 *a		
	1328	1.819 *b		
6 [1]	302	0.006 *a	Similar to the above except cooling cycles.	Volk, H. F., et al., 1969
	302	0.006 *b		
	376	0.045 *a		
	376	0.119 *b		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
6 (cont.)	472	0.077 *a		
[1]	472	0.307 *b		
	573	0.164 *a		
	573	0.562 *b		
	668	0.446 *a		
	668	0.783 *b		
	771	0.619 *a		
	771	0.883 *b		
	870	0.746 *a		
	870	0.969 *b		
	970	0.927 *a		
	970	1.102 *b		
	1071	1.094 *a		
	1071	1.249 *b		
	1167	1.268 *a		
	1167	1.403 *b		
	1271	1.455 *a		
	1271	2.584 *b		
	1328	1.562 *a		
	1328	1.731 *b		
7	436	0.263	Similar to the above except	Volk, H. F., et al.,
[1]	572	0.519	transverse expansion; zero point	1969
	680	0.717	correction is 0.032%.	
	782	0.908		
	877	1.103 *		
	988	1.301		
	1093	1.502 *		
	1273	1.901		
	1401	2.109 *		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
8 [2]	293	0.000 *	Continuous electrodeposition of Ni on unidirectional Thornel 50 graphite fibers; fiber composition not explicitly mentioned; it may be either 37 volume % from the sample composition for transverse measurements or 46 volume % from their statement that this effort was essentially a repetition of their earlier work; specimens were plate like and prepared from aligned nickel cooled yarn by hot pressing at 1050°C and 2000-3500 psi pressure for one hour; first heating cycle in the longitudinal direction; data on the coefficient of thermal expansion also reported; permanent longitudinal deformation was not observed; data extracted from figure.	Volk, H. F., Nara, H. R., and Hanley, D. P., 1971
	378	0.015		
	475	0.053		
	537	0.076		
	562	0.080		
	576	0.082		
	675	0.087		
	773	0.092		
	874	0.097		
	973	0.103		
	1075	0.108		
	1179	0.113		
	1275	0.118		
9 [2]	304	0.001 *	Similar to the above except first cooling cycle; contraction-expansion in the interval 125-350°C is retraced without evidence of hysteresis; the cycling between 425° and 125°C generates a hysteresis loop which is due to elastic-plastic deformation in the matrix which is a requirement for ratcheting, thus	Volk, H. F., et al., 1971
	378	0.002		
	475	0.003		
	523	0.005		
	541	0.006		
	551	0.007 *		
	561	0.010 *		
	576	0.018		
	634	0.037		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
9 (cont.) [2]	674	0.047	expansion-contraction between 125° and 350°C is elastic and does not cause permanent deformation; elastic-plastic behavior is encountered between 125-425°C and ratcheting is evident and composite properties deteriorates.	
	774	0.062		
	875	0.079		
	973	0.090		
	1075	0.100		
	1176	0.109		
10 [2]	329	0.004 *	Similar to the above except second heating cycle.	Volk, H. F., et al., 1971
	378	0.011		
	476	0.035		
	522	0.048		
	541	0.050		
	561	0.053		
	577	0.055		
	674	0.061		
	774	0.067 *		
	807	0.068 *		
	819	0.068		
	844	0.068		
	875	0.069		
	973	0.073		
	1075	0.079		
	1176	0.084		
	1273	0.090		
11 [2]	324	0.002 *	Similar to the above except second cooling cycle.	Volk, H. F., et al., 1971
	338	0.003		
	378	0.005 *		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
11 (cont.) [2]	475	0.010		
	578	0.015 *		
	626	0.019		
	676	0.022		
	734	0.029		
	775	0.036		
	875	0.050		
	972	0.062		
	1075	0.072		
	1176	0.082		
12 [2]	331	0.002	Similar to the above except average of third, fourth, and fifth heating cycles.	Volk, H. F., et al., 1971
	378	0.006		
	477	0.010 *		
	576	0.015 *		
	676	0.021		
	775	0.027		
	875	0.034		
	973	0.039		
	1077	0.045		
	1175	0.053		
	1273	0.062		
13 [2]	331	0.003 *	Similar to the above except third, fourth, and fifth cooling cycle.	Volk, H. F., et al., 1971
	378	0.008		
	475	0.021		
	577	0.032		
	676	0.038		
	775	0.040 *		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
13 (cont.) [2]	875	0.038		
	973	0.041		
	1077	0.047		
	1176	0.055		
	1273	0.062 *		
14 [2]	300	0.001 *	Similar to the above except longitudinal expansion after 100 cycles.	Volk, H. F., et al., 1971
	360	0.006		
	411	0.014		
	466	0.027		
	514	0.038		
	537	0.042		
	559	0.045		
	605	0.048		
	695	0.053		
	778	0.058		
15 [2]	303	0.001 *	Similar to the above except longitudinal expansion after specimen cycled 500 times; expansion-contraction of a specimen cycled 500 times over the interval 125-425°C show a symetric hysteresis loop and reduced expansion is evident which infers that it is possible to ascertain from thermal expansion measurements the possibility of a composite undergoing permanent deformation and the cycle bond required for such a change.	Volk, H. F., et al., 1971
	374	0.002		
	472	0.006		
	575	0.009		
	672	0.013		
	774	0.017		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
16 [2]	301	0.001 *	Similar to the above except longitudinal expansion after 1000 cycles.	Volk, H. F., et al., 1971
	373	0.004 *		
	472	0.010 *		
	576	0.015		
	670	0.020 *		
	775	0.024		
17 [2]	307	0.009	Similar to the above except transverse expansion; heating cycle.	Volk, H. F., et al., 1971
	359	0.059		
	410	0.131		
	450	0.206		
	530	0.359		
	632	0.571		
	719	0.752		
	808	0.924		
	870	1.052		
	963	1.242		
	1039	1.392		
	1089	1.492		
	1151	1.614		
	1210	1.729		
	1249	1.798		
18 [2]	304	0.031 *	Similar to the above except cooling cycle.	Volk, H. F., et al., 1971
	314	0.037		
	351	0.078 *		
	396	0.143		
	438	0.218		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	<u>THERMAL LINEAR EXPANSION</u> (cont.)	
18 (cont.) [2]	478	0.290 *		
	526	0.387		
	584	0.509		
	624	0.590		
	666	0.674		
	710	0.756		
	749	0.827		
	806	0.905 *		
	872	1.024		
	957	1.202		
	1032	1.355		
	1083	1.461		
	1139	1.576		
	1187	1.676		
19 [3]	297	0.001	Unidirectionally reinforced plates made by laying up rectangular bundles of nickel coated Thornel 50 graphite yarn by a layer technique procedure; bundles were then placed inside a rectangular "picture frame" cans and compressed to about 50 % theoretical density before hermetic sealing by electron beam melting for subsequent hot isostatic pressing; expansion measured parallel to filament orientation; first heating cycle; 50 volume % filament; data extracted from figure.	Niesz, D. E., 1968
	301	0.003 *		
	325	0.014 *		
	373	0.040		
	473	0.087		
	510	0.100 *		
	527	0.103		
	540	0.105 *		
	561	0.103 *		
	573	0.101		
	673	0.075		
	773	0.049		
	873	0.028		
	904	0.025 *		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
19 (cont.) [3]	973	0.024		
	1072	0.023		
	1176	0.025		
	1229	0.025 *		
	1253	0.022		
20 [3]	293	0.000 *	Similar to the above except first cooling cycle; zero point correction is 0.075%.	Niesz, D. E., 1968
	297	-0.001 *		
	303	-0.002 *		
	323	-0.009 *		
	373	-0.013		
	384	-0.013 *		
	403	-0.013		
	421	-0.011 *		
	474	0.000		
	574	0.022		
	673	0.040		
	774	0.048		
	873	0.052		
	974	0.055		
	1073	0.061		
	1175	0.076		
	1231	0.089		
21 [3]	296	0.001 *	Similar to the above except second heating cycle.	Niesz, D. E., 1968
	301	0.003		
	325	0.014		
	373	0.040		
	472	0.082		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
21 (cont.) [3]	548	0.098		
	573	0.099 *		
	644	0.096		
	673	0.092 *		
	773	0.076		
	873	0.058		
	972	0.054		
	1073	0.057		
	1174	0.066		
	1220	0.069 *		
	1252	0.069		
22 [3]	290	0.000	Similar to the above except second cooling; zero point correction is 0.0215%.	Niesz, D. E., 1968
	296	0.000 *		
	302	-0.002 *		
	323	-0.008 *		
	337	-0.011 *		
	373	-0.016		
	393	-0.017 *		
	413	-0.017 *		
	474	-0.010		
	573	0.012		
	672	0.030		
	771	0.040		
	875	0.045		
	974	0.053		
	1073	0.061		
	1174	0.073		
	1223	0.082		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
23 [3]	293	0.000 *	Similar to the above except expansion measured perpendicular to filament orientation; zero point correction -0.037%.	Niesz, D. E., 1968
	308	0.032		
	369	0.160		
	424	0.270 *		
	481	0.402		
	538	0.540		
	589	0.730		
	646	0.899		
	701	1.020		
	761	1.132		
	815	1.224		
	873	1.333		
	927	1.420		
	986	1.507		
	1039	1.590		
	1097	1.668		
	1154	1.773		
24 [3]	293	0.000 *	Similar to the above except cooling cycle; zero point correction -0.082%.	Niesz, D. E., 1968
	294	0.000 *		
	366	0.160 *		
	426	0.284		
	478	0.393 *		
	535	0.521 *		
	591	0.620		
	646	0.750		
	702	0.873		
	762	0.992		
	816	1.092		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
24 (cont.) [3]	872	1.200		
	928	1.307		
	985	1.417		
	1042	1.518		
	1097	1.630		
	1154	1.723		
25 [4]	306	0.005 *	25 volume % graphite fibers nickel matrix obtained by chemical deposition of nickel on the fibers and subsequent thermal diffusion composition of fibers; test specimen 30 x 4 x 3 mm plates; heated in argon atmosphere at 3 degrees min^{-1}; accuracy ±5°, dilatometry; heating experiment measurement direction not reported; data extracted from figure.	Salibekov, S. E., Portnoi, K. I., and Chubarov, V. M. 1972
	345	0.100		
	400	0.200		
	479	0.277		
	516	0.296		
	592	0.314		
	645	0.300		
	678	0.274		
	724	0.231		
	801	0.143		
	878	0.081		
	927	0.052		
	988	0.026		
	1028	0.008		
	1077	-0.002		
26 [4]	307	0.009 *	Similar to the above except cooling cycle; zero point correction is 0.305%.	Salibekov, S. E., 1972
	395	0.083		
	466	0.149		
	542	0.208		
	621	0.245		
	716	0.257		

TABLE 31. DATA ON THE THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
26 (cont.) [4]	817	0.261		
	933	0.265		
	989	0.265		
	1035	0.266		
	1074	0.288		
27 [4]	309	0.005 *	Similar to the above except 45 volume % graphite fibers and heating cycle.	Salibekov, S. E., 1972
	404	0.027		
	474	0.039		
	544	0.046		
	596	0.050		
	673	0.051		
	774	0.044		
	878	0.033		
	958	0.023		
	1022	0.019		
	1065	0.012		
28 [4]	294	0.001 *	Similar to the above except cooling cycle; zero point correction is 0.136%.	Salibekov, S. E., 1972
	438	0.035		
	526	0.076		
	557	0.098		
	606	0.109		
	649	0.120		
	744	0.121		
	839	0.118		
	927	0.118		
	1013	0.119		
	1071	0.130		

*Not shown in figure.

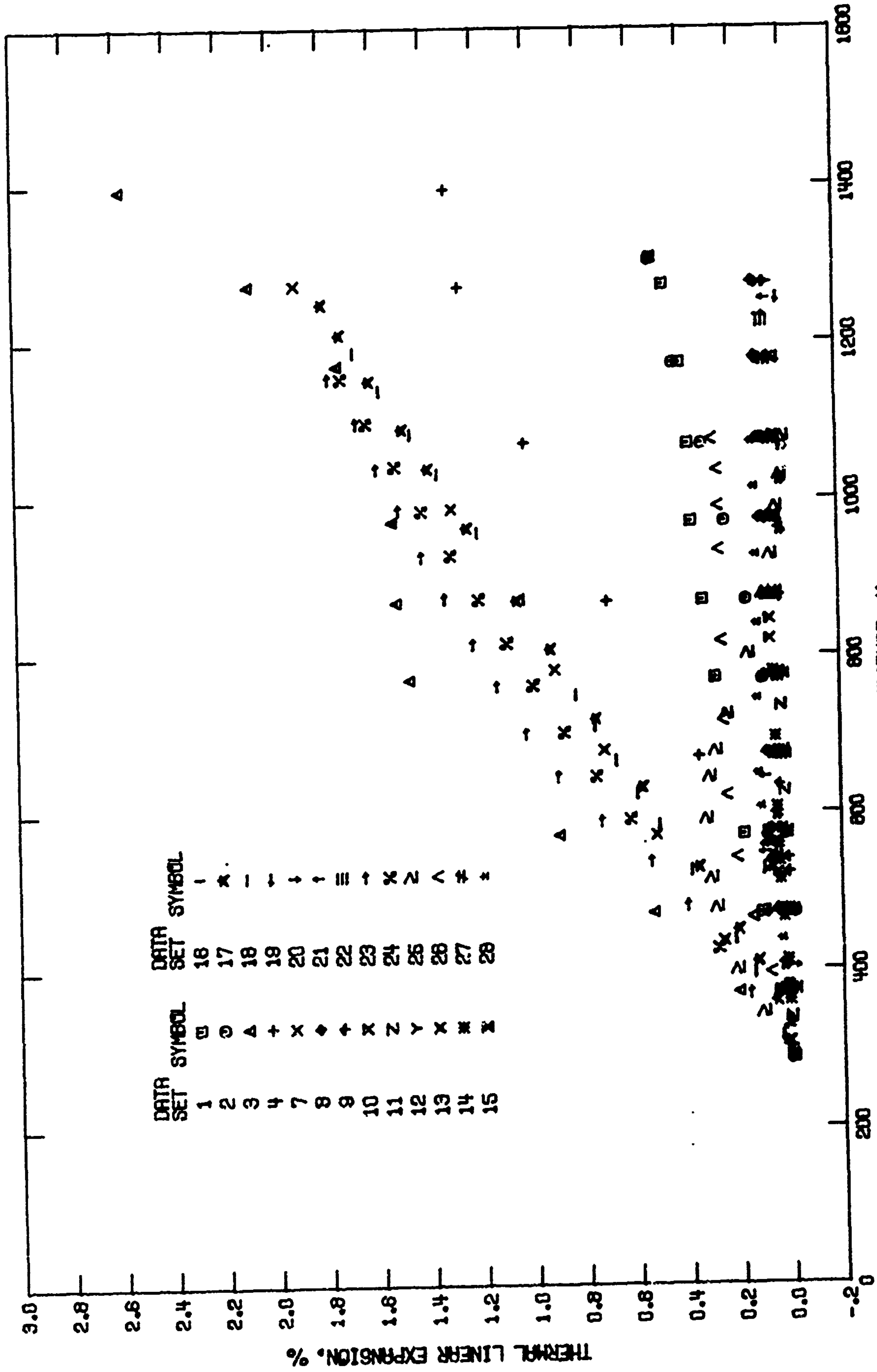

FIGURE 45. THERMAL LINEAR EXPANSION OF GRAPHITE FIBER, NICKEL MATRIX COMPOSITE.

5.3. SiC FILAMENT, NICKEL MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Chuang [1] reported a value of $8.4 \times 10^{-6}\ K^{-1}$ for the mean coefficient of thermal expansion between room temperature and 873 K for 30 volume percent SiC filaments in a nickel matrix.

REFERENCE

1. Chuang, K.C., U.S. Air Force Rept. AFML-TR-66-330, 59 pp., 1966. [AD-802 423]

TABLE 32. DATA ON THE THERMAL LINEAR EXPANSION OF SiC FILAMENT, NICKEL MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	293 873	0.000 * 0.487 *	30 volume % SiC-Ni matrix composites fabricated by electroforming techniques; SiC filaments are relatively uniformly spaced in the Ni matrix, direction of the measurements unspecified; values calculated from mean coefficient.	Chuang, K. C., 1986

*Not shown in figure.

5.4. TUNGSTEN WIRE, KhN60V MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Karpinos et al. [1] reported thermal expansion data for composites containing alternate sheets of KhN60V (25%Cr, 15%W and 4%Fe, nickel base) alloy matrix and unidirectionally oriented VA tungsten (nominally 100% pure) wires of 0.18 mm diameter prepared by dynamic densification under a friction hammer. The Composites contained 8.6, 18, 22, and 25 volume percent of reinforcement. Since The thermal expansion of the matrix material is much higher than that of the fiber material at low temperatures where the matrix makes the main contribution to the expansion of the composite, the expansion increases in accordance with the expansion of the pure matrix. As the temperature is increased, the matrix becomes plastic and the thermal expansion begins to fall after passing through a maximum. The temperature corresponding to this maximum decreases with increasing fiber content. Karpinos et al. [1] also proposed a method for calculating the coefficient of thermal expansion of composites with unidirectionally oriented fibers in which the elastic-plastic behavior of the components are taken into account.

REFERENCE

1. Karpinos, D.M., Tuchinskii, L.I., Miroshnikova, T.K., and Vishnyakov, L.R., Sov. Powder Met. Metal Ceram., (1), 62-5, 1974.

TABLE 33. DATA ON THE THERMAL LINEAR EXPANSION OF TUNGSTEN WIRE, KhN60V MATRIX

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	293	0.000	18 volume % tungsten composites; KhN60V(V Zh98), a nickel base alloy with 25% Cr and 15% W alloy matrix reinforced with VA tungsten wires; the extent to which the tungsten reinforcement dissolves in this material during prolonged exposure to temperatures of 1000 and 1200°C is virtually zero, specimen composed of matrix sheets alternating with layers of unidirectionally arranged VA tungsten wires of 0.18 mm diameter were prepared by dynamic densification under a friction hammer; expansion measured with chevenard dilatometer on a 3 mm square by 40 mm long bar specimens in which the fibers were oriented parallel to the longitudinal axis heating rate in argon atmosphere was 10 C min^{-1}; measurement direction not reported; values calculated from tabulated values of mean coefficient.	Karpinos, D. M., Tuchinskii, L. I., Miroshnikova, T. K., and Vishnyakov, L. R., 1974
	373	0.063		
	473	0.155		
	573	0.266		
	673	0.376		
	773	0.480		
	873	0.609		
	973	0.750		
	1073	0.835		
	1173	0.870		
	1273	0.870		
2 [1]	373	0.042	Similar to the above except 25 volume % tungsten.	Karpinos, D. M., et al., 1974
	473	0.140		
	573	0.233		

TABLE 33. DATA ON THE THERMAL LINEAR EXPANSION OF TUNGSTEN WIRE, KhN60V MATRIX (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
2 (cont.)	673	0.337		
[1]	773	0.430		
	873	0.547		
	973	0.655		
	1073	0.716		
	1173	0.742		
	1273	0.762		
3	353	0.048	Similar to the above except 22 volume % tungsten; values obtained by integrating graphically reported values of instantaneous coefficient.	Karpinos, D. M., et al., 1974
[1]	456	0.130		
	553	0.219		
	656	0.323		
	710	0.380		
	758	0.431		
	807	0.484		
	861	0.543 *		
	904	0.588		
	959	0.643		
	1002	0.682		
	1056	0.723		
4	353	0.075	Similar to the above except 8.6 volume % tungsten.	Karpinos, D. M., et al., 1974
[1]	461	0.209		
	558	0.340		
	661	0.489		
	758	0.638		
	861	0.803		
	963	0.971		
	1072	1.151		
	1153	1.282		
	1261	1.444		

*Not shown in figure.

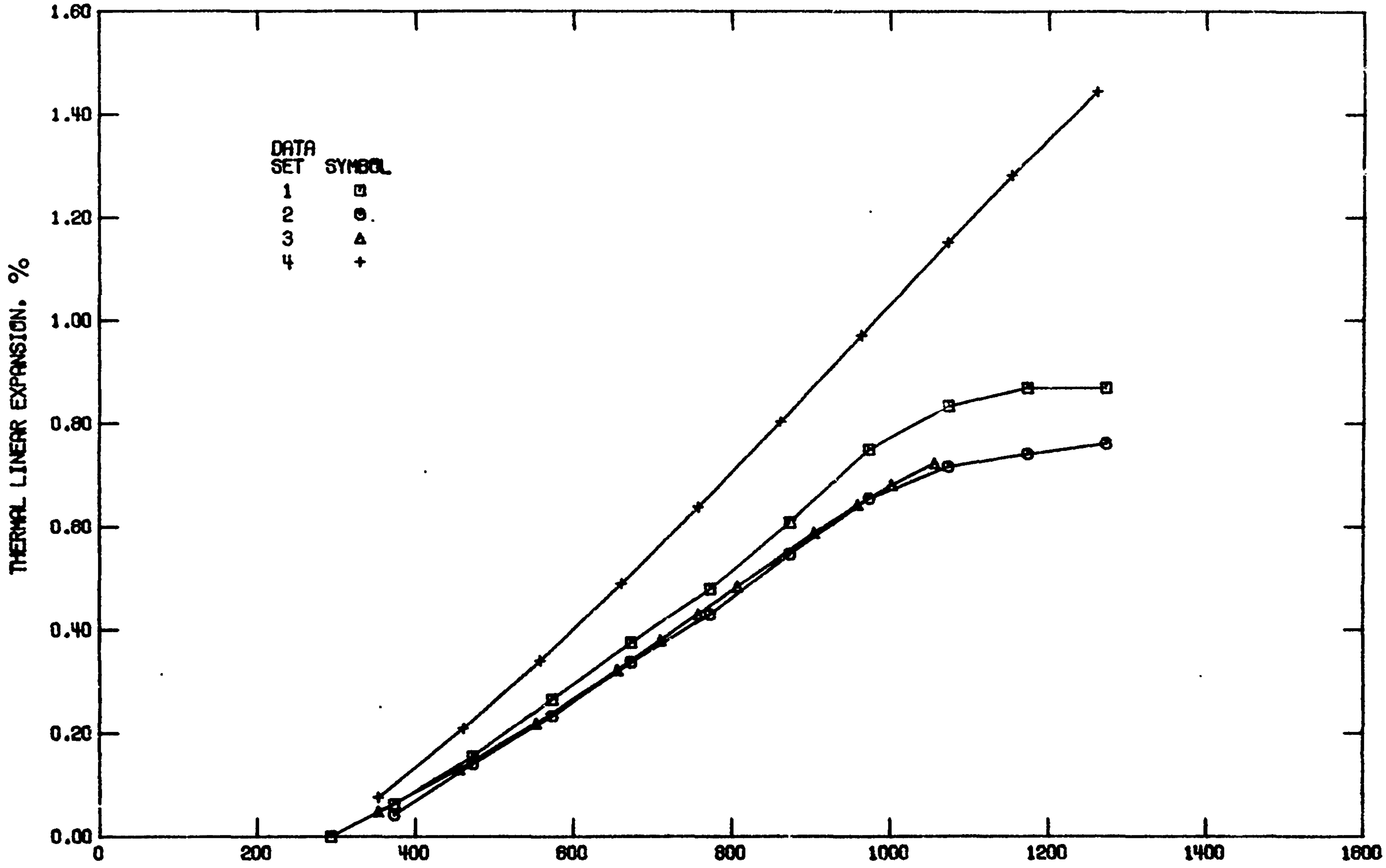

FIGURE 46. THERMAL LINEAR EXPANSION OF TUNGSTEN WIRE, KHN60V MATRIX COMPOSITE.

5.5. TUNGSTEN FIBER, ZhS6K NICKEL ALLOY MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Salibekov et al. [1] reported thermal expansion data for a composite containing 40 volume percent tungsten fibers in ZhS6K nickel alloy matrix. This composite expands to about 0.745 percent at 1127 K.

REFERENCE

1. Salibekov, S.E., Portnoi, K.I., and Chubarov, V.M., High Temp., 10(4), 702-6, 1972.

TABLE 34. DATA ON THE THERMAL LINEAR EXPANSION OF TUNGSTEN FIBER, ZhS6K NICKEL ALLOY MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	306	0.005	40 volume % tungsten fibers ZhS6K nickel alloy composite obtained by vacuum impregnation of plaited tungsten fibers of 0.4 mm diameter with liquid alloy; test specimen 30 x 4 x 3 mm plates, heated in argon atmosphere at 3 degrees min^{-1}; accuracy ±5%, dilatometry; average of heating and cooling experiments; measurement direction not reported, data extracted from figure; zero point correction is 0.005%.	Salibekov, S. E., Portnoi, K. I., and Chubarov, V. M., 1972
	388	0.076		
	470	0.122		
	564	0.188		
	674	0.280		
	748	0.338		
	813	0.396		
	874	0.455		
	944	0.521		
	1005	0.596		
	1078	0.675		
	1111	0.712		
	1127	0.745		

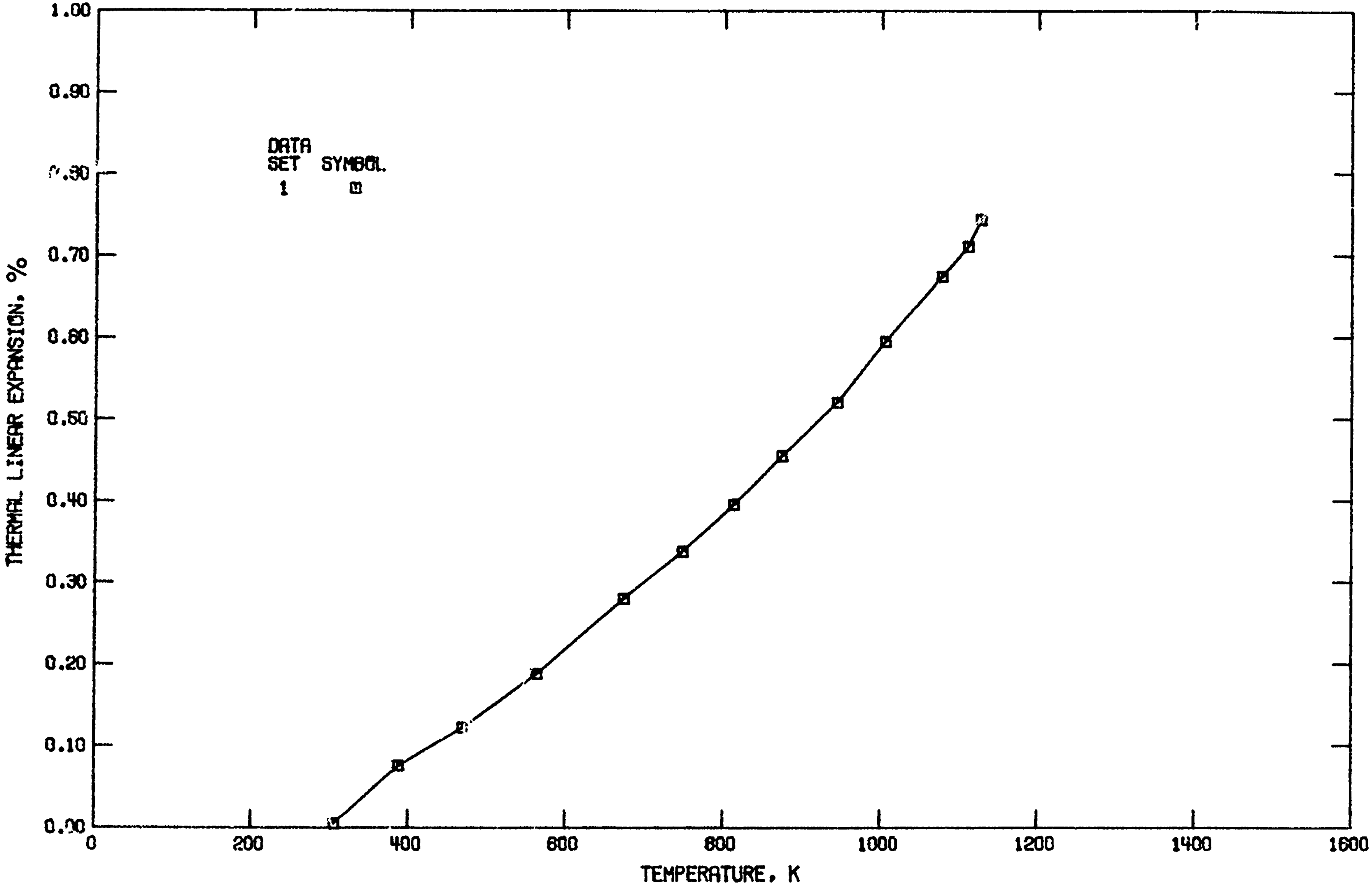

FIGURE 47. THERMAL LINEAR EXPANSION OF TUNGSTEN FIBER, ZHS6K NICKEL ALLOY MATRIX COMPOSITE.

5.6. THORIA DISPERSED, NICKEL-CHROMIUM ALLOY MATRIX COMPOSITE

THERMAL EMITTANCE

There is one reference [1] in which data for the emittance of a thoria dispersed nickel-chromium alloy matrix composite are reported, and over the temperature 1255 to 1478 K there is a slow decrease in emittance as the temperature increases. For a thoria dispersed nickel-chromium alloy with an addition of aluminum and yttrium, the emittance at 1478 K shows no difference compared with that of the alloy without that addition.

ELECTRICAL RESISTIVITY

Only one data point on the electrical resistivity at room temperature is available for a composite with nickel-chromium alloy (20 volume % Cr) matrix [1].

REFERENCES

1. Centolanzi, F.J., NASA Rept. NASA-TM-X-62015, 52 pp., 1971.
2. Wolf, S.M., J. Metals, 19(6), 22-8, 1967.

TABLE 35. DATA ON THE THERMAL EMITTANCE AND ELECTRICAL RESISTIVITY OF THORIA DISPERSED, Ni-Cr ALLOY MATRIX COMPOSITE

[Thermal Emittance, ϵ; Electrical Resistivity, ρ, 10^{-8} Ω m]

Data Set [Ref.]	Temp.	Prop.		Specifications and Remarks	Author(s), Year
	T	ε		THERMAL EMITTANCE	
1 [1]	1235 1478	0.85 0.70		Ni-20Cr-$2ThO_2$; manufactured by Fansteel Corp.; emittance determined from radiometric measurements; Thermodot TD-6BT Radiation Thermometer used; uncertainty ±0.05.	Centolanzi, F. J., 1971
2 [1]	1478	0.70		Ni-16Cr-$2ThO_2$ with addition of aluminum and yttrium; proprietary alloy manufactured by Fansteel Corporation; emittance determined from radiometric measurements; Thermodot TD-6BT Radiation Thermometer used; uncertainty ±0.05.	Centolanzi, F. J., 1971
3 [1]	1478	0.70		Manufactured by Fansteel Corp.; Ni-20Cr-$2ThO_2$; emittance determined from radiometric measurements; Thermodot TD-6BT Radiation Thermometer used; uncertainty ±0.05.	Centolanzi, F. J., 1971
	T	ρ		ELECTRICAL RESISTIVITY	
1 [2]	293	108.	*	20.0 volume % Cr added to Ni matrix.	Wolf, S. M., 1967

*Not shown in figure.

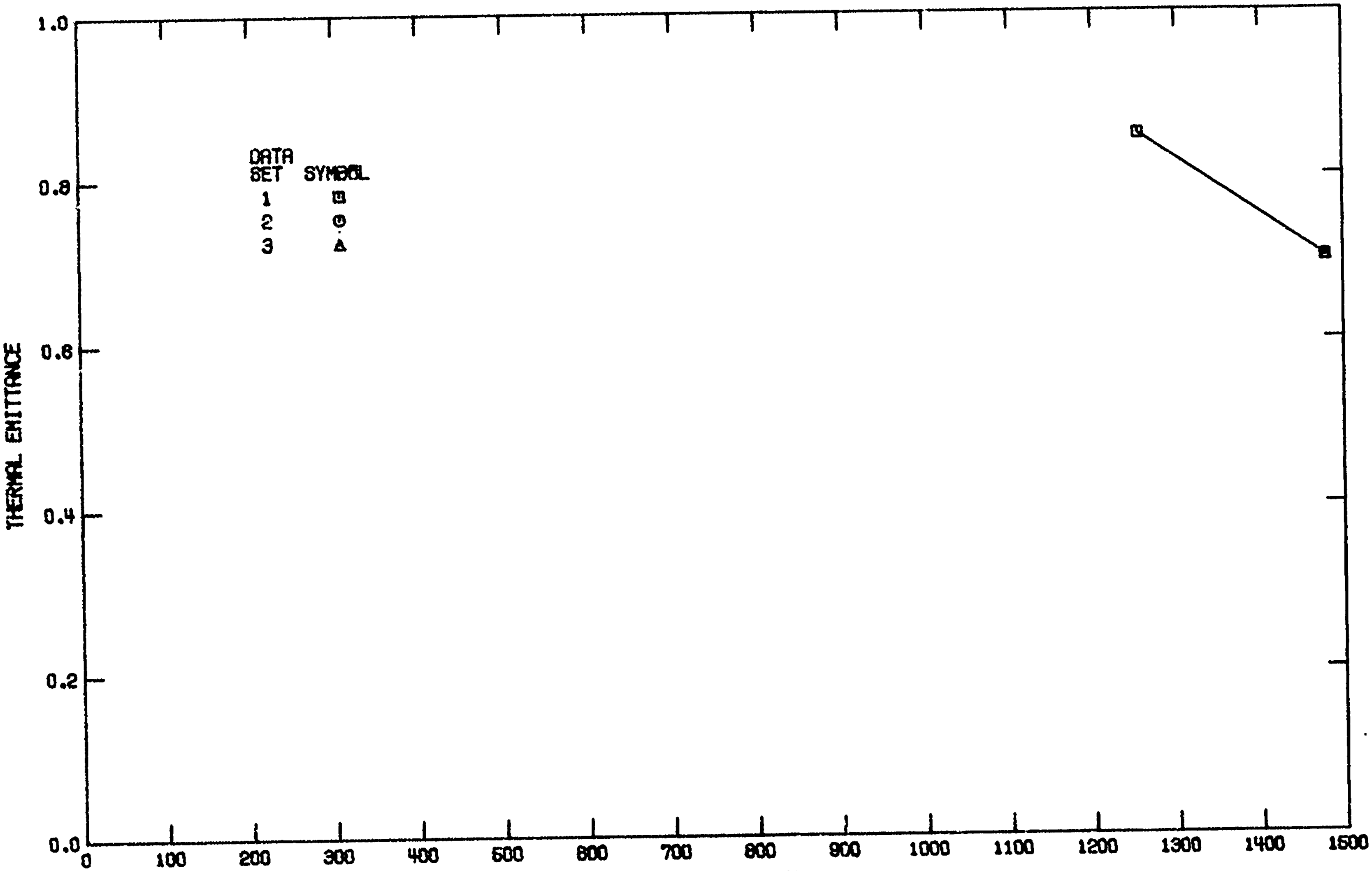

FIGURE 48. THERMAL EMITTANCE OF THORIA DISPERSED, NICKEL-CHROMIUM ALLOY MATRIX COMPOSITE.

CHAPTER 6

TITANIUM AND TITANIUM ALLOY MATRIX COMPOSITES

6.1. MOLYBDENUM FIBER, TITANIUM MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Karpinos et al. [1] reported thermal expansion data for composites containg 10-30 volume percent MCH molybdenum (99.9% technically pure) fibers in a VT1-0 titanium (99.9% commercially pure) matrix. Thermal expansion along the fiber orientation decreases with increasing molybdenum fiber content. Karpinos et al. [1] also reported the data for composite specimens with angle between fiber direction and the longitudinal axis of the specimen ranging from 25 to 90 degrees. Salibekov et al. [2] reported that a composite made by sintering and subsequent extrusion of a mixture of titanium powder and discrete 20 volume percent molybdenum fibers expands to about 0.438 percent at 842 K.

REFERENCES

1. Karpinos, D.M., Kadyrov, V.Kh., Klimenko, V.S., Fefer, V.Ya., and Miroshnikova, T.K., Sov. Powder Met. Metal. Ceram., (4), 301-3, 1974.
2. Salibekov, S.E., Portnoi, K.I., and Chubarov, V.M., High Temp., 10(4), 702-6, 1972.

TABLE 36. DATA ON THE THERMAL LINEAR EXPANSION OF MOLYBDENUM FIBER, TITANIUM MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	193	-0.075	VT1-0 titanium base composite reinforced with Mch molybdenum; composites prepared by tecnique of elevated temperature densification of packs composed of alternating matrix foil and reinforcing fiber layers; 10 volume % Mch molybdenum; thermal expansion of composite was measured on 4 mm square by 60 mm long prismatic specimens cut from densified blanks oriented parallel to the direction of fiber orientation; volume fraction of fibers determined on micrographs of specimen cross sections; thermal expansion measured on chevenard type dilatometer in argon atmosphere; heating rate 2°C min^{-1}; values calculated by integrating graphically reported values of instantaneous coefficient.	Karpinos, D. M., Kadyrov, V. Kh., Klimenko, V. S., Fefer, V. Ya., and Miroshnikova, T. K., 1974
	232	-0.047		
	279	-0.011 *		
	327	0.027 *		
	382	0.073		
	437	0.120		
	496	0.173		
	535	0.211		
	583	0.258		
	642	0.317		
	689	0.365		
	736	0.414		
	784	0.464		
	831	0.515		
	874	0.564		
	926	0.624		
2 [1]	327	0.025	Similar to the above except 25 volume % molybdenum fibers.	Karpinos, D. M., et al., 1974
	378	0.062 *		
	457	0.120		
	504	0.156		
	551	0.193		
	591	0.225		

TABLE 38. DATA ON THE THERMAL LINEAR EXPANSION OF MOLYBDENUM FIBER, TITANIUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
2 (cont.) [1]	646	0.272		
	689	0.308		
	736	0.349		
	784	0.392		
	827	0.431		
	874	0.475		
	926	0.525		
3 [1]	189	-0.060	Similar to the above except 30 volume % molybdenum fibers.	Karpinos, D. M., et al., 1974
	232	-0.035		
	275	-0.011		
	327	0.020 *		
	390	0.061		
	425	0.084		
	457	0.104		
	535	0.156		
	583	0.189		
	642	0.230		
	689	0.265		
	736	0.300		
	780	0.333		
	827	0.370		
	878	0.410		
	926	0.448		
4 [1]	300	0.005 *	Similar to the above specimen except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 25 degrees.	Karpinos, D. M., et al., 1974
	400	0.079 *		

TABLE 38. DATA ON THE THERMAL LINEAR EXPANSION OF MOLYBDENUM FIBER, TITANIUM MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
5 [1]	300 400	0.005 * 0.079 *	Similar to the above except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 45 degrees.	Karpinos, D. M., et al., 1974
6 [1]	300 400	0.006 * 0.089 *	Similar to the above specimen except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 65 degrees.	Karpincs, D. M., et al., 1974
7 [1]	300 400	0.005 * 0.083 *	Similar to the above specimen except the angle between the fiber direction in a specimen and specimen's longitudinal axis is 90 degrees; values calculated from the graphically reported mean coefficient.	Karpinos, D. M., et al., 1974
8 [2]	290 355 432 500 574 630 672 730 774 804 842	-0.003 0.044 0.107 0.164 0.224 0.268 0.306 0.347 0.383 0.405 0.438	20 volume % molybdenum fibers titanium matrix composites obtained by sintering and subsequent extrusion of a mixture of titanium powder and discrete molybdenum fibers; test specimen 30 x 4 x 3 mm plates; heated in argon at 3 degree min^{-1}; accuracy ±5°; dilatometry; average of heating and cooling experiments; measurement direction not reported; data extracted from figure.	Salibekov, S. E., Portroi, K. I., and Chubarov, V. M., 1972

*Not shown in figure.

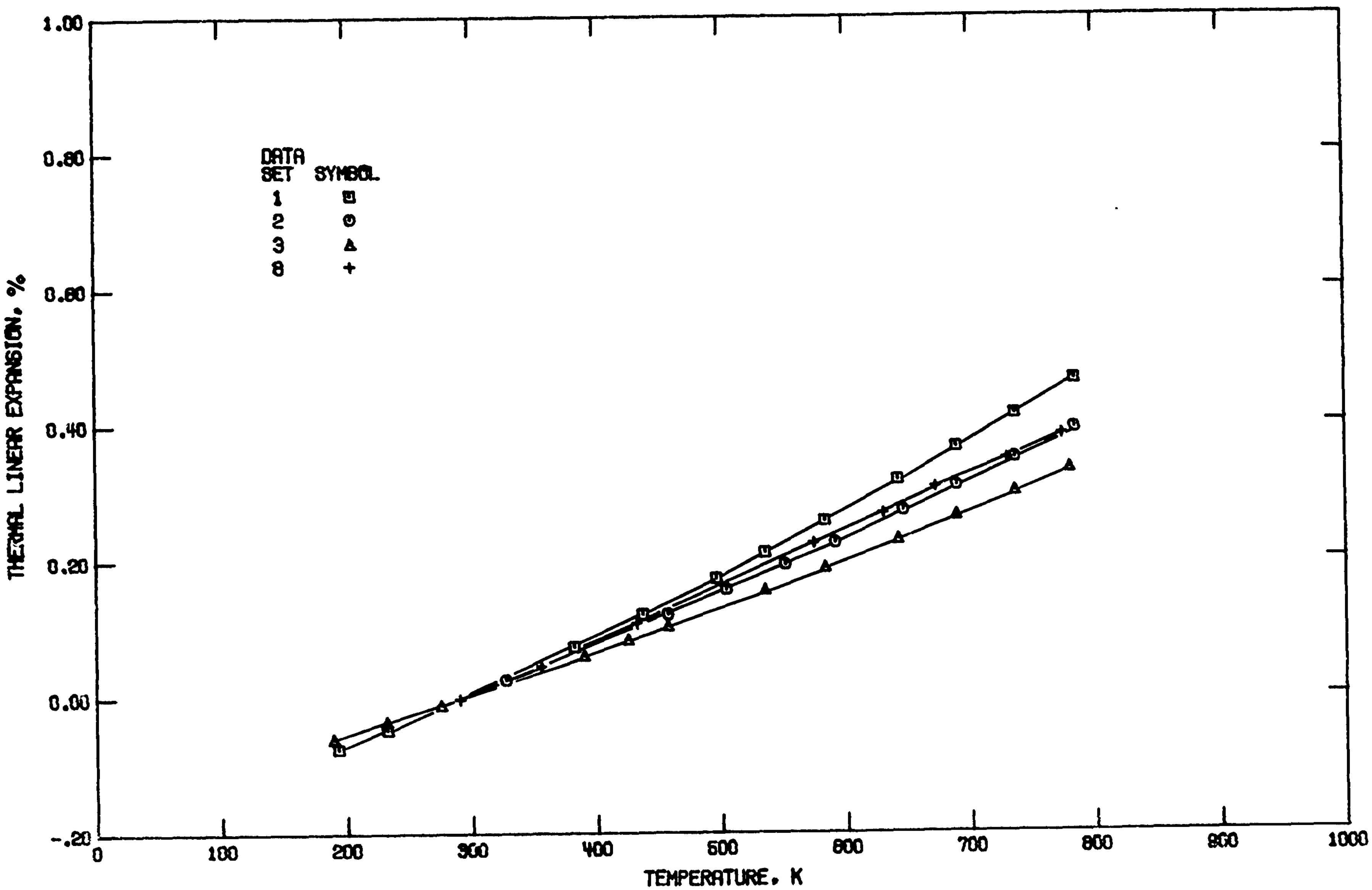

FIGURE 49. THERMAL LINEAR EXPANSION OF MOLYBDENUM FIBER, TITANIUM MATRIX COMPOSITE.

6.2. BORSIC FILAMENT, Ti-6Al-4V ALLOY MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Hofer et al. [1] reported thermal expansion data for a composite fabricated by TRW Inc. Thermal expansion along the longitudinal axis is lower than that along the transverse axis.

THERMAL CONDUCTIVITY

There is one reference [1] in which the thermal conductivity of a Borsic fiber Ti-6Al-4V alloy matrix composite having fiber content of ~50 volume percent is reported. The data are for heat flow both in the parallel (to the fiber) and in the perpendicular directions, and for the temperature range ~80 - 800 K. The authors also gave substantial details on the fabrication of the composite.

REFERENCE

1. Hofer, K.E., Jr., Rao, N., and Larsen, D., U.S. Air Force Rept. AFML-TR-72-205-Pt-2, 470 pp., 1974. [AD-A015 907]

TABLE 37. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FILAMENT, Ti-6Al-4V ALLOY MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %; Thermal Conductivity, λ, W m^{-1} K^{-1}]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1	108	-0.067	Composite fabricated by TRW Inc.,	Hofer, K. E., Jr.,
[1]	143	-0.061 *	as follows: Borsic filaments were	Rao, N., and
	199	-0.044	wound on a 16 inch diameter drum	Larsen, D., 1974
	255	-0.024	mound in a filament-winding machine;	
	310	0.004	filament spacing was accurately	
	367	0.034	maintained to provide desired	
	424	0.071	filament volume; filaments were drawn	
	480	0.110	through a glass nozzle in the process	
	534	0.159	which added a polystyrene binder	
	590	0.199 *	coating to the fiber; collimated	
	645	0.245	fiber mat is next cut and inserted	
	699	0.290 *	between two titanium foils; this	
	752	0.337	monolayer was then placed between two	
			stainless steel or molybdenum	
			separator which is coated with	
			graphite and BN antiadhesive	
			coatings; the assembly then placed	
			inside a stainless steel capsule	
			which is then evaluated; the capsule	
			was hot pressed (to break down	
			polystyrene into gaseous products);	
			assembly is bonded for a period of	
			time at high pressure and	
			temperature; surface is etched to a	
			50 volume % thickness; monolayers	
			were stacked between 20 mil. thick	
			double plates and subjected to high	

TABLE 37. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FILAMENT, Ti-6Al-4V ALLOY MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	<u>THERMAL LINEAR EXPANSION</u> (cont.)	
1 (cont.) [1]			pressure and temperature; average of five samples in the 0° fiber orientation; heating cycle; data on the coefficient of expansion also reported; data extracted from figure.	
2 [1]	109	-0.064 *	Similar to the above except cooling cycle.	Hofer, K. E., Jr., et al., 1974
	143	-0.058		
	199	-0.041 *		
	255	-0.019		
	310	0.010		
	367	0.040 *		
	422	0.077		
	479	0.118		
	534	0.161 *		
	590	0.202		
	645	0.248 *		
	699	0.293		
3 [1]	111	-0.107	Similar to the above except heating cycle in the 90° fiber orientation direction.	Hofer, K. E., Jr., et al., 1974
	146	-0.094 *		
	202	-0.069		
	259	-0.034		
	314	0.005 *		
	369	0.047		
	424	0.091		
	480	0.136 *		
	535	0.187		
	592	0.240		

TABLE 37. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FILAMENT, Ti-6Al-4V ALLOY MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
3 (cont.)	646	0.295		
[1]	701	0.346 *		
	755	0.400		
4	113	-0.106 *	Similar to the above except cooling cycle in the 90° fiber orientation direction.	Hofer, K. E., Jr., et al., 1974
[1]	147	-0.093		
	202	-0.065 *		
	259	-0.030		
	314	0.001 *		
	369	0.041 *		
	425	0.091 *		
	480	0.138		
	535	0.187 *		
	592	0.243		
	646	0.295 *		
	701	0.346		
	T	λ	THERMAL CONDUCTIVITY	
1	102	4.25	Supplied by TRW Inc.; 5.7 mil borsic fiber with a polystyrene binder coating was wound on a 16 inch diameter drum; the fiber mat was then cut and inserte d between Titanium foils; the monolayer was placed between stainless steel or molybdenum separator, with graphite and boron nitride antiadhesive coating; assembly placed in evacuated stainless steel capsule; capsule then hot pressed to decompose the	Hofer, K. E. Jr., Rao, N., and Larsen, D., 1974
[1]	143	4.32		
	252	4.57		
	364	5.00		
	471	5.70		
	584	6.44		
	694	7.14		
	794	7.83		

TABLE 37. DATA ON THE THERMOPHYSICAL PROPERTIES OF BORSIC FILAMENT, Ti-6Al-4V ALLOY MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY (cont.)	
1 (cont.) [1]			polystyrene in a dynamic vacuum; bonding was achieved by pressing at the bonding temperature for a period of time; the monolayer was then etched and stacked between 20 mil thick double plates; the assembly was subjected to pressure at elevated temperature; fiber volume content ~50%; measured with heat flow parallel to fiber direction; smoothed values from graph.	
2 [1]	82	4.05	The above with heat flow perpendicular to fiber direction; smoothed values from graph.	Hofer, K. E., Jr., et al., 1974
	142	4.12		
	252	4.43		
	364	4.90		
	471	5.44		
	584	6.00		
	694	6.59		
	807	7.12		
	815	7.16		

*Not shown in figure.

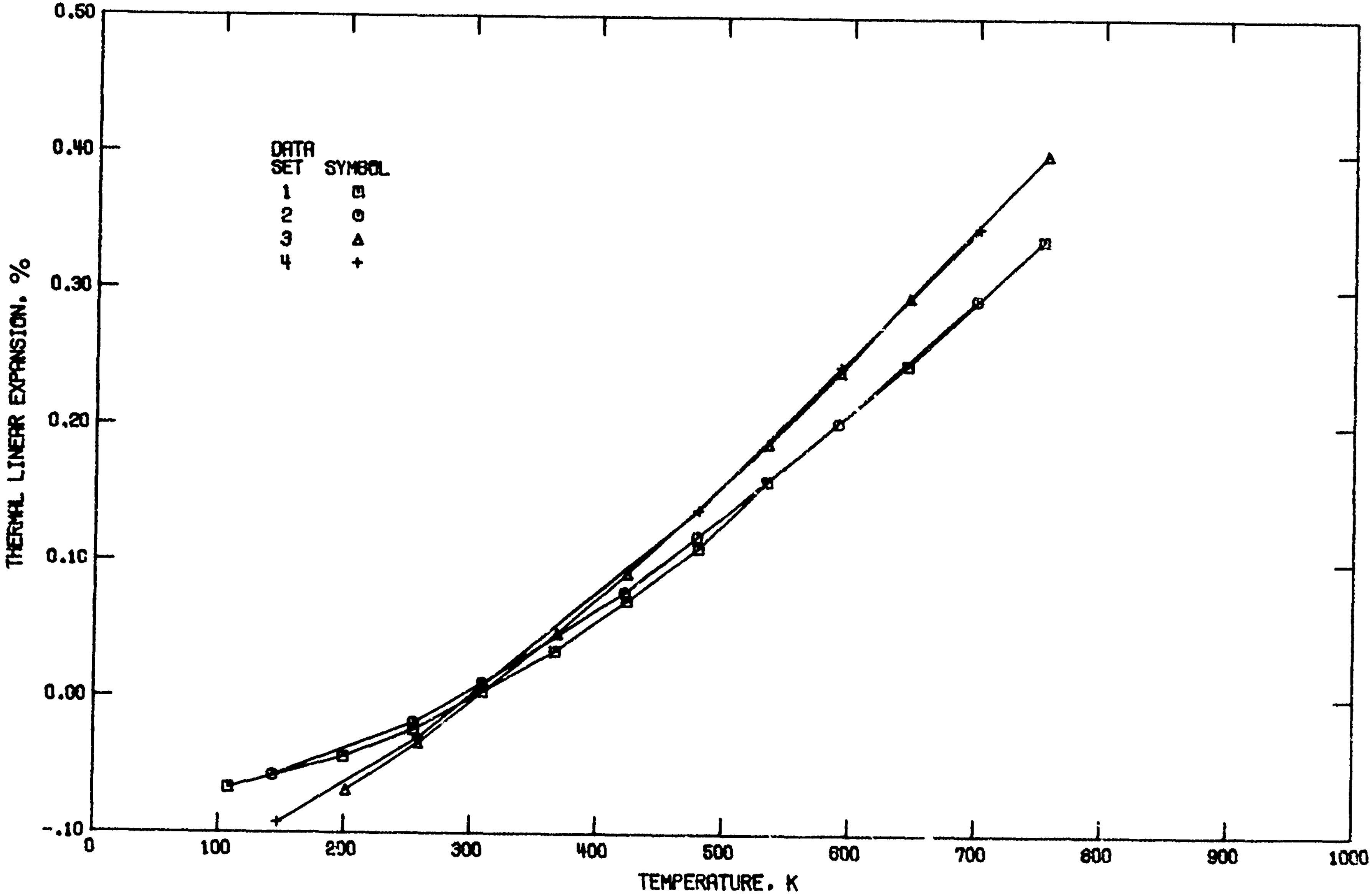

FIGURE 50. THERMAL LINEAR EXPANSION OF BORSIC FILAMENT. TI-6AL-4V ALLOY MATRIX COMPOSITE.

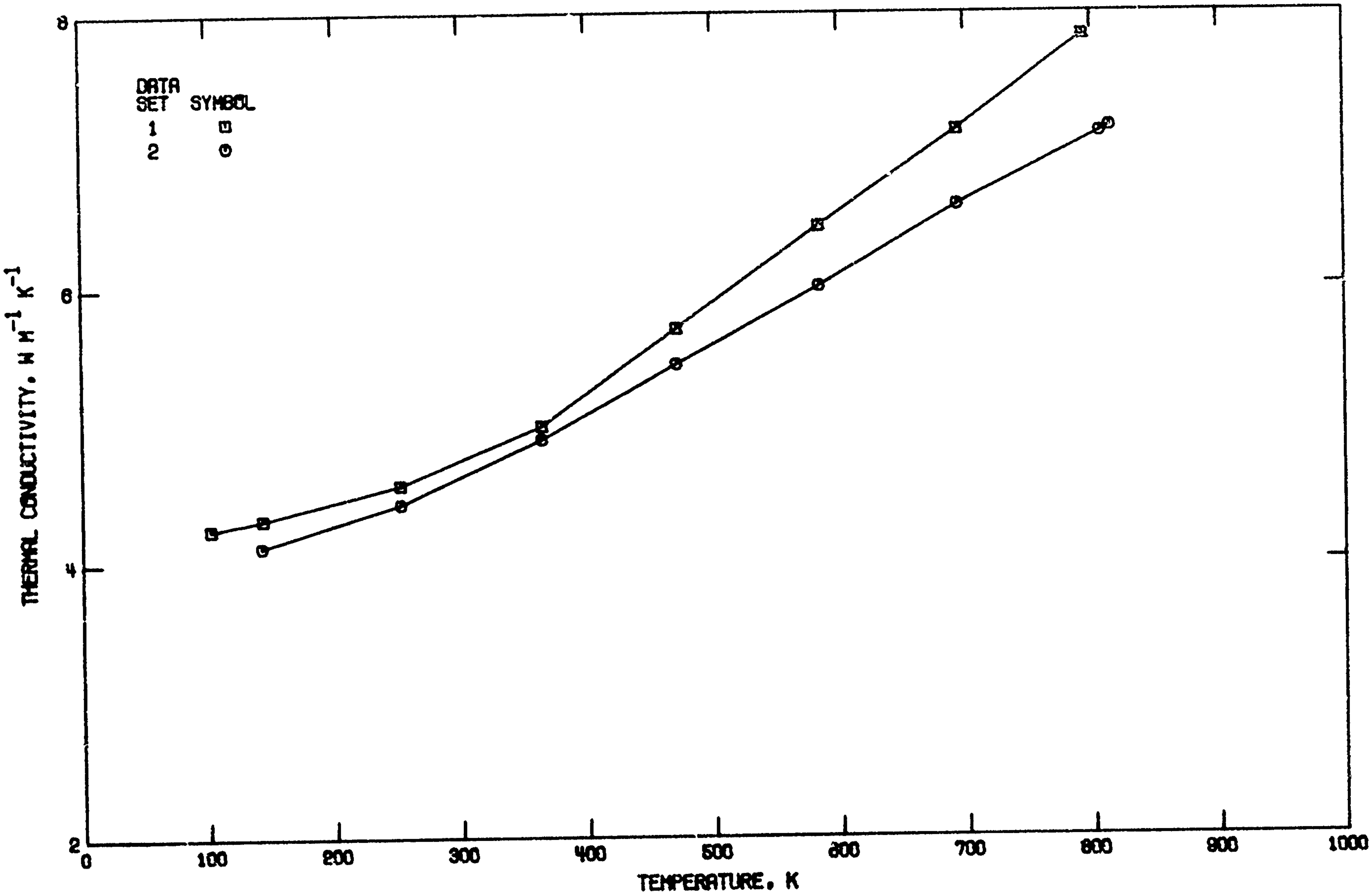

FIGURE 51. THERMAL CONDUCTIVITY OF BORSIC FILAMENT. TI-6AL-4V ALLOY MATRIX COMPOSITE.

CHAPTER 7

TUNGSTEN AND TUNGSTEN ALLOY MATRIX COMPOSITES

7.1. COPPER INFILTRATED, TUNGSTEN MATRIX COMPOSITE

THERMAL CONDUCTIVITY

There is one reference [1] in which the thermal conductivity of sintered tungsten infiltrated with copper is reported. The tungsten is 80% dense. No other information is given on the fabrication of the specimen or on its final porosity.

REFERENCE

1. Kammer, E.W., Smith, H., and Olcott, E., Naval Research Lab. Rept. NRL-6005, 51 pp., 1963. [AD-430 879]

TABLE 38. DATA ON THE THERMAL CONDUCTIVITY OF COPPER INFILTRATED, TUNGSTEN MATRIX COMPOSITE

[Thermal Conductivity, λ, W m^{-1} K^{-1}]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY	
1 [1]	571	120.4	80% dense sintered tungsten, infiltrated with copper; cylindrical specimen 1-5/8 inches in diameter and 2 inches long.	Kammer, E. W., Smith, H., and Olcott, E., 1963
	576	120.4		
	652	127.5		
	652	127.7		
	716	123.5		
	718	124.4		
	760	127.3		
	762	126.8		
	767	124.4		
	767	127.3		
	895	124.8		
	992	118.9		
	1001	118.5		
	1008	119.6		
	1088	124.3		
	1091	124.8		
	1201	124.4		
	1201	121.6		
	1252	125.2		
	1270	122.7		

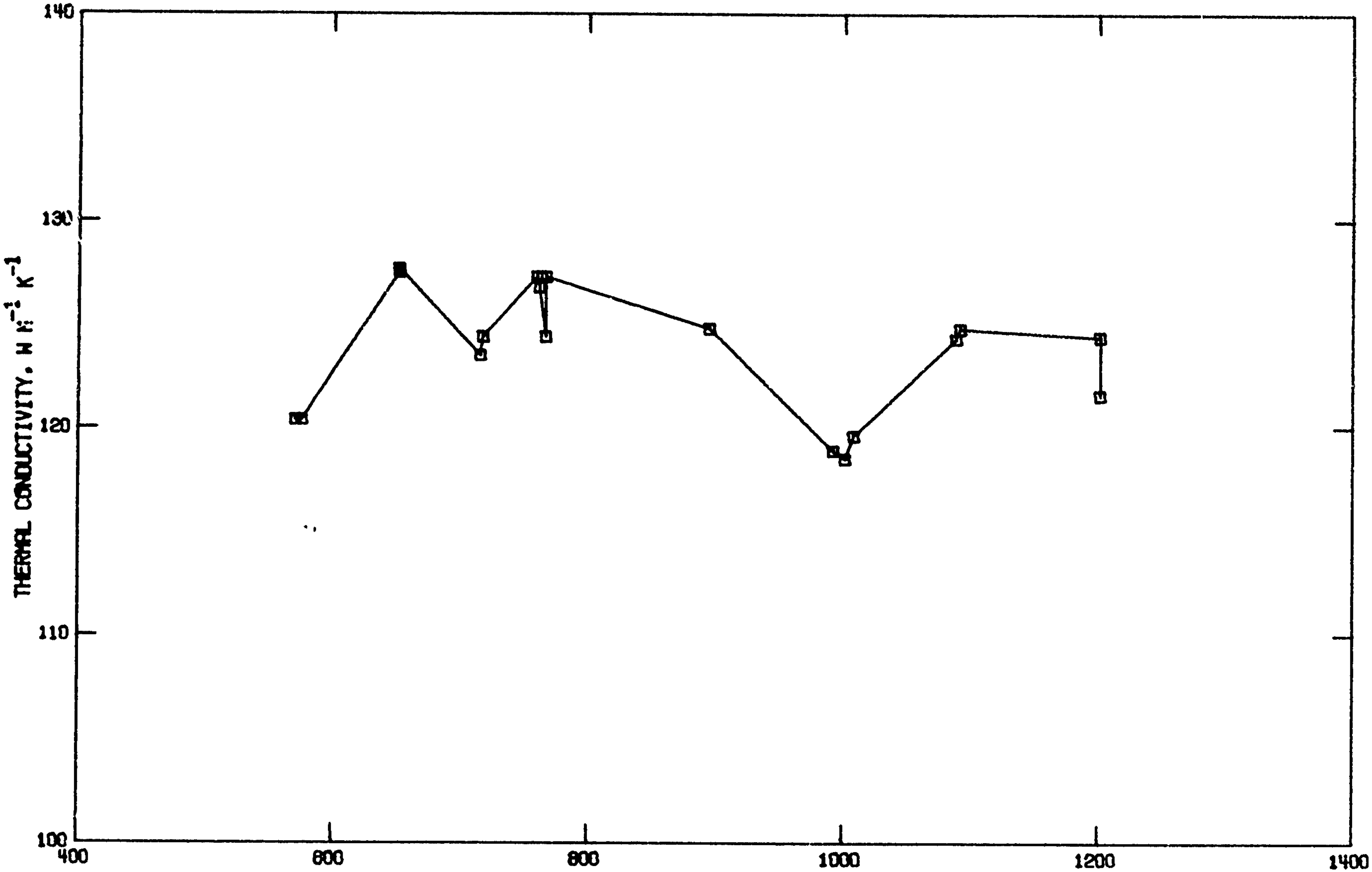

FIGURE 52. THERMAL CONDUCTIVITY OF COPPER INFILTRATED, TUNGSTEN MATRIX COMPOSITE.

7.2. MOLYBDENUM FIBER, TUNGSTEN MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Owen [1] reported thermal expansion data for composites containing 70 volume percent commercially pure molybdenum wires in a sintered tungsten matrix. This was one of the materials developed by the Department of the Navy. A value of 0.492 was reported for the percent thermal expansion of this material at 1253 K. Owen [2] also reported a value of 0.452 at 1273 K for the percent thermal expansion of a similar composite for solid propellent rocket motor nozzle application.

THERMAL CONDUCTIVITY

There is one reference [2] in which the thermal conductivity of sintered tungsten reinforced with molybdenum wire is reported. No information is given on the composition, fabrication, and other characterization of the specimen.

SPECIFIC HEAT

Owen [1] reported a value of 158 J kg^{-1} K^{-1} at 293 K for a composite containing 18 weight percent molybdenum fiber.

REFERENCES

1. Owen, L., Jr., Air Force Rocket Propulsion Lab. Rept., 30 pp., 1966. [AD-377 060]
2. Owen, L. Jr., U.S. Air Force Rept. on Proj., AF-3059, 40 pp., 1967. [AD-379 508]

TABLE 39. DATA ON THE THERMOPHYSICAL PROPERTIES OF MOLYBDENUM FIBER, TUNGSTEN MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %; Thermal Conductivity, λ, W m^{-1} K^{-1}; Specific Heat, c_p, J Kg^{-1} K^{-1}]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	298	0.002	Composite is a sintered tungsten matrix reinforced with commercial pure molybdenum wires as developed by Dept. of Navy; 70 volume % tungsten matrix consisting of 60 % 34 microns, 30 % 10-microns, and 10 % 1-micron powder; 30 volume % TZM molybdenum fibers at 10-mil. diameter by 1/4 inch long in random orientation; three specimen 0.157 inch diameter by 0.197 inch long each having one flat end and one high angle, conical end were hot pressed to 85 % theoretical density; there were placed between fused silica optical flats in a fused silica chambers which was placed in Gaertner resistance furnace and 80 microns pressure; expansion rate measured by interferometer; system showed no oxidation; values calculated from tabular values of mean coefficients.	Owen, L., Jr., 1966
	373	0.030 *		
	473	0.076		
	573	0.121		
	673	0.172		
	773	0.225		
	873	0.279		
	973	0.333		
	1073	0.390		
	1173	0.445		
	1253	0.492		
2 [2]	373	0.030	TZM molybdenum fiber reinforced tungsten composite material used as an insert in solid propellant, rocket motor nozzle; nozzle contained a pure	Owen, L., Jr., 1967
	573	0.114		
	773	0.205		
	1273	0.452		

TABLE 39. DATA ON THE THERMOPHYSICAL PROPERTIES OF MOLYBDENUM FIBER, TUNGSTEN MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.		Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$		THERMAL LINEAR EXPANSION (cont.)	
2 (cont.) [2]				tungsten overlay over the entire internal contour, while substrate consisted of molybdenum fiber reinforced tungsten; composition not given; measurement direction not reported; values calculated from graphically reported values of instantaneous coefficient.	
	T	λ		THERMAL CONDUCTIVITY	
1 [2]	323	136.		Sintered W matrix reinforced with commercial pure Mo wire; data supplied by Melpar, Inc.; values from table.	Owen, L., Jr., 1967
	433	128.			
	590	121.			
	773	113.			
	1026	107.			
	1218	99.			
	1473	94.			
	1698	97.			
	T	c_p		SPECIFIC HEAT	
1 [1]	293	158.	*	Material same as the one used for expansion; 18 weight % molybdenum, and 82 weight % tungsten; water calorimetry.	Owen, L., Jr., 1966

*Not shown in figure.

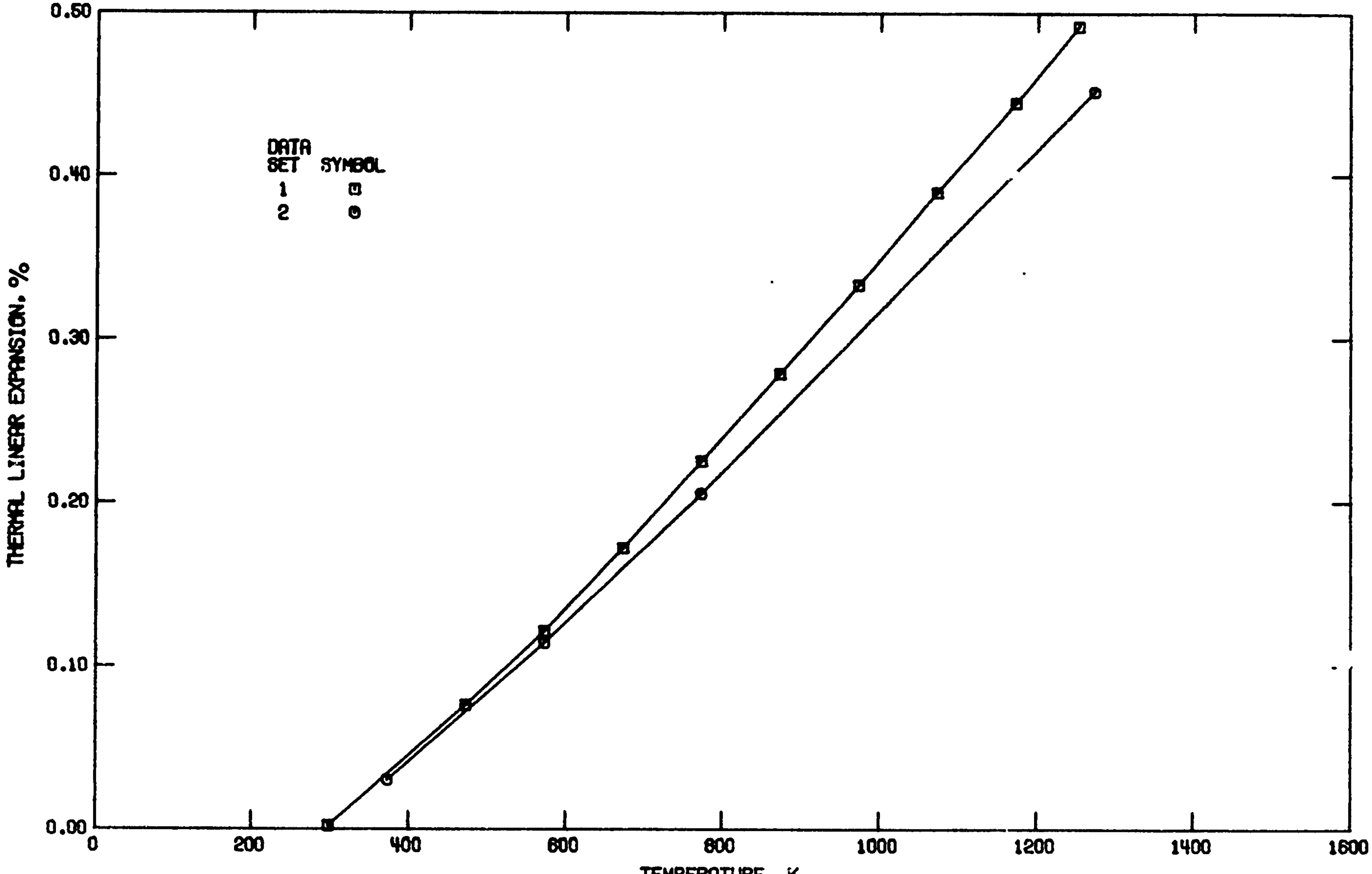

FIGURE 53. THERMAL LINEAR EXPANSION OF MOLYBDENUM FIBER. TUNGSTEN MATRIX COMPOSITE.

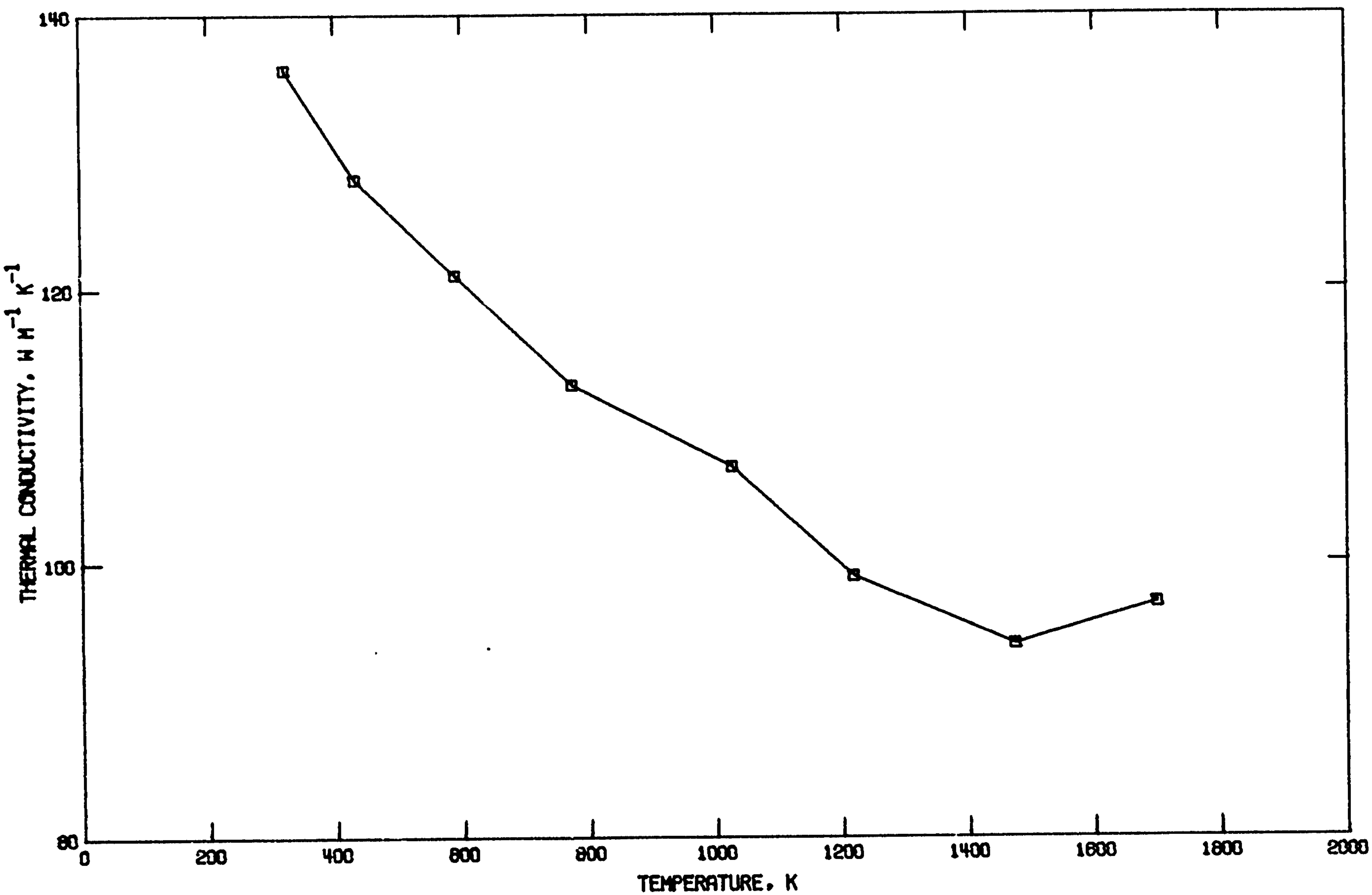

FIGURE 54. THERMAL CONDUCTIVITY OF MOLYBDENUM FIBER, TUNGSTEN MATRIX COMPOSITE.

7.3. SILVER INFILTRATED, TUNGSTEN MATRIX COMPOSITE

THERMAL CONDUCTIVITY

There is one reference [1] in which the thermal conductivity of sintered tungsten infiltrated with silver is reported. The tungsten is 80% dense. No other information is given on the fabrication of the specimen or on its final porosity.

REFERENCE

1. Kammer, E.W., Smith, H., and Olcott, E., Naval Research Lab. Rept. NRL-6005, 51 pp., 1963. [AD-430 879]

TABLE 40. DATA ON THE THERMAL CONDUCTIVITY OF SILVER INFILTRATED, TUNGSTEN MATRIX COMPOSITE

[Temperature, T, K; Thermal Conductivity, λ, W m^{-1} K^{-1}]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	λ	THERMAL CONDUCTIVITY	
1 [1]	553	116.5	80% dense sintered tungsten infiltrated with silver; cylindrical specimen 1-5/8 inch in diameter and 2 inches long.	Kammer, E. W., Smith, H., and Olcott, E., 1963
	558	116.9		
	737	118.3		
	741	119.1		
	950	113.8		
	961	115.1		
	1045	114.3		
	1072	113.9		
	1217	117.9		

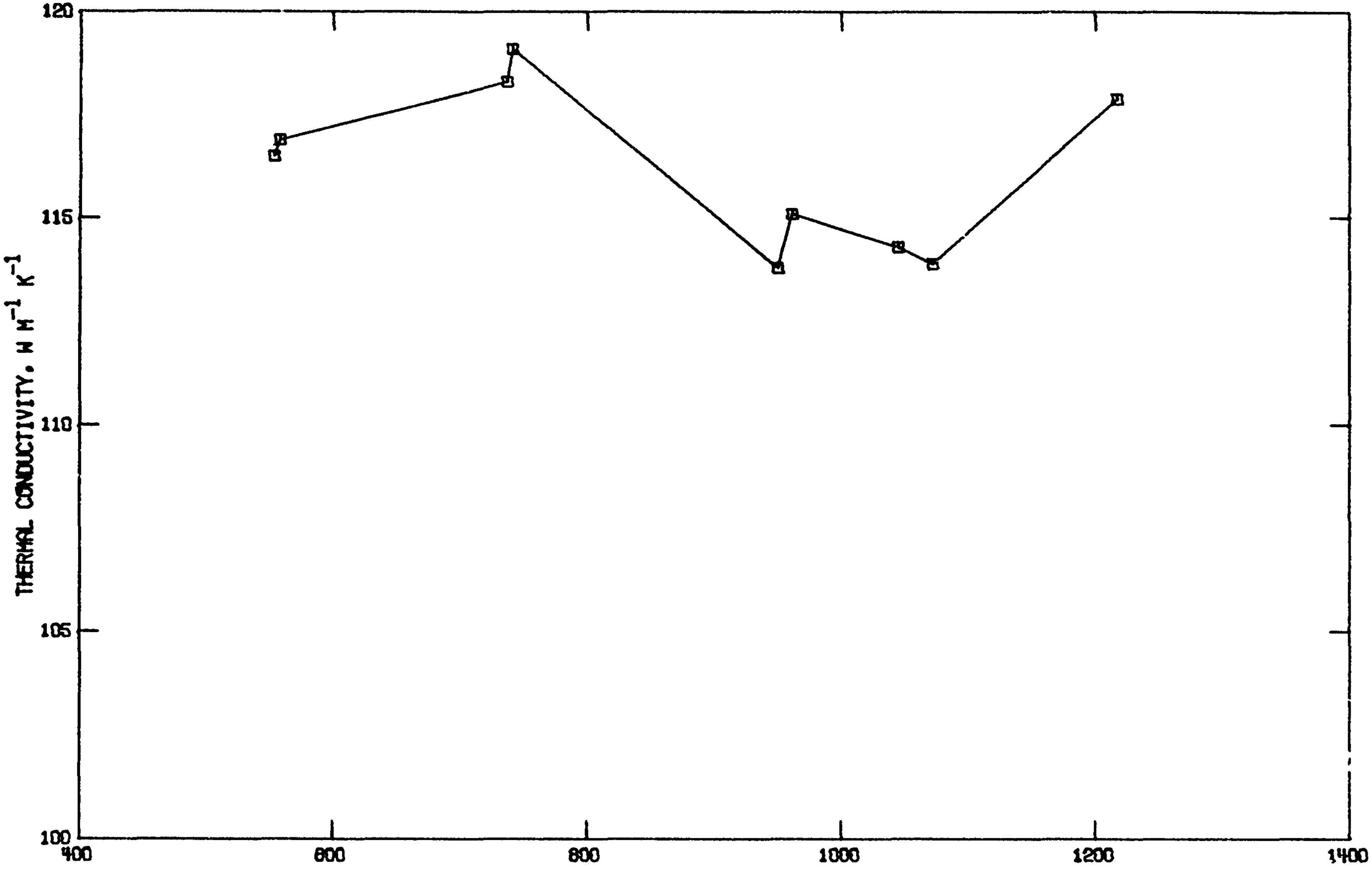

FIGURE 55. THERMAL CONDUCTIVITY OF SILVER INFILTRATED, TUNGSTEN MATRIX COMPOSITE.

CHAPTER 8

ZINC AND ZINC ALLOY MATRIX COMPOSITES

8.1. 'E' GLASS FIBER, ZINC MATRIX COMPOSITE

THERMAL LINEAR EXPANSION

Whitehurst et al. [1] and Lockwood [2] reported thermal expansion data for a composite material containing 20 volume percent 'E' glass fibers in zinc matrix.

REFERENCES

1. Whitehurst, H.B., Michener, J.W., and Lockwood, P.A., Proc. 6th Sagamore Army Mater. Res. Conf., 248-76, 1960. [AD-233 158]

2. Lockwood, P.A., Owens-Corning Fiberglas Corp. Rept., 164 pp., 1960. [AD- 274 530]

TABLE 41. DATA ON THE THERMAL LINEAR EXPANSION OF 'E' GLASS FIBER,ZINC MATRIX COMPOSITE

[Temperature, T, K; Thermal Linear Expansion, $\Delta L/L_0$, %]

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION	
1 [1]	321	0.016	'E' glass fibers 20 volume %; 0.0006 inch in diameter and parallel oriented; zinc matrix composites have been heated several times or normalized at their service temperature before experiments; heating experiment; measurement direction not reported, data extracted from figure.	Whitehurst, H. B., Michener, J. W., and Lockwood, P. A., 1960
	348	0.052		
	373	0.085		
	386	0.103		
	410	0.134		
	439	0.163		
	454	0.180		
	469	0.194		
	500	0.225		
	529	0.252		
	553	0.267		
	566	0.278		
	587	0.283		
	600	0.290		
2 [1]	316	0.010	Similar to the above except cooling curve.	Whitehurst, H. B., et al., 1960
	349	0.041		
	373	0.062		
	396	0.084		
	421	0.109		
	447	0.133		
	469	0.154		
	491	0.176		
	512	0.196		
	537	0.221		
	566	0.250		
	586	0.270		
	601	0.284		
	614	0.295		

TABLE 41. DATA ON THE THERMAL LINEAR EXPANSION OF 'E' GLASS FIBER,ZINC MATRIX COMPOSITE (continued)

Data Set [Ref.]	Temp.	Prop.	Specifications and Remarks	Author(s), Year
	T	$\Delta L/L_0$	THERMAL LINEAR EXPANSION (cont.)	
3 [2]	293	0.000	0.0006 inch diameter 20 % 'E' glass fibers; parallel oriented; vacuum injection casting; heating cycle; measurement direction not reported; data extracted from figure.	Lockwood, P. A., 1960
	311	0.020		
	365	0.094		
	401	0.135		
	422	0.158		
	457	0.198		
	477	0.215		
	512	0.247		
	533	0.263		
	561	0.282		
	586	0.294		
	621	0.304		
4 [2]	294	0.001	Similar to the above except cooling cycle.	Lockwood, P. A., 1960
	311	0.016		
	364	0.067		
	423	0.120		
	477	0.170		
	532	0.220		
	586	0.270		

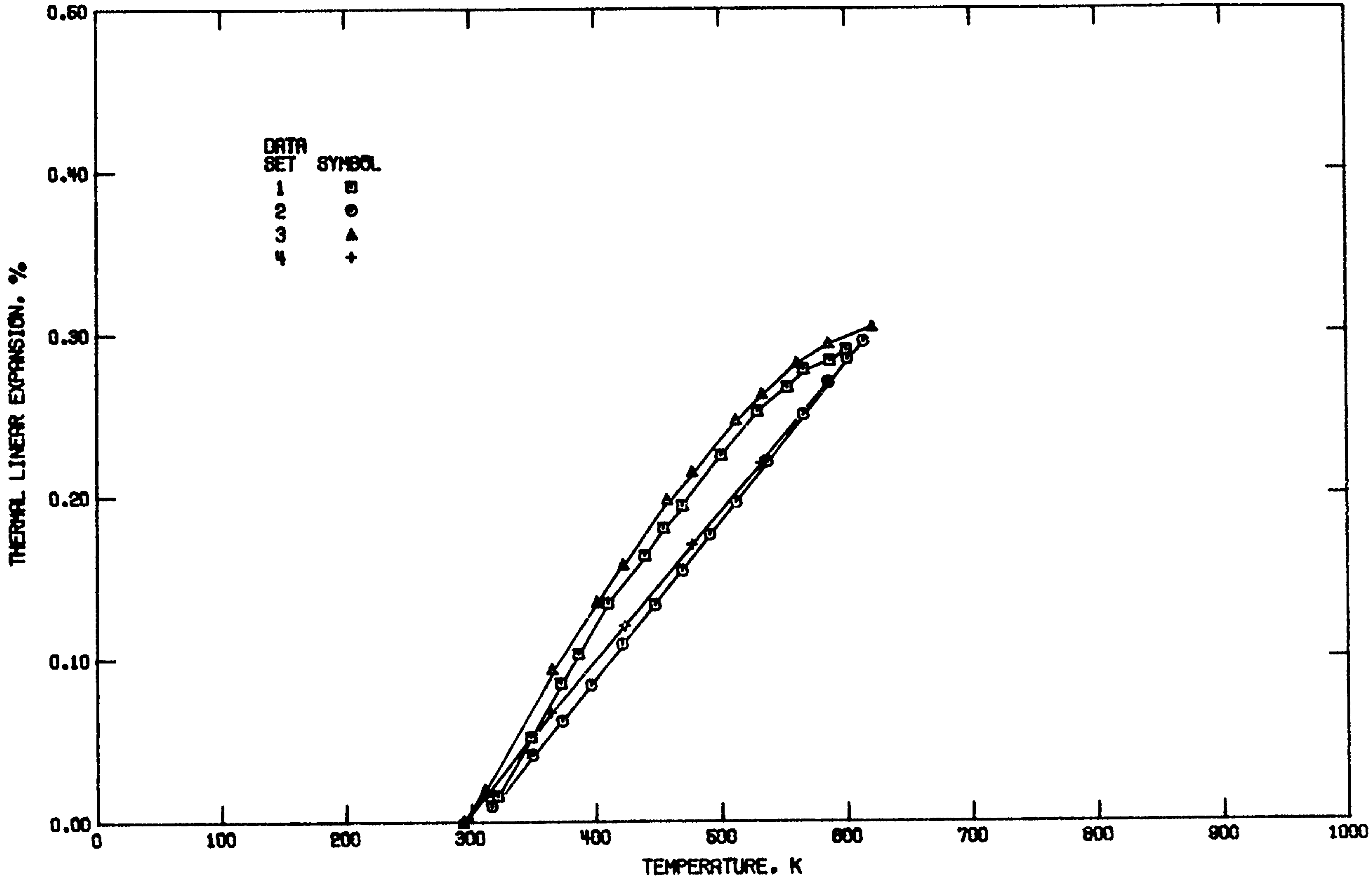

FIGURE 56. THERMAL LINEAR EXPANSION OF E GLASS FIBER. ZINC MATRIX COMPOSITE.

INDEX TO MATERIALS AND PROPERTIES

[$\Delta L/L_0$ = Thermal Linear Expansion, λ = Thermal Conductivity
c_p = Specific Heat, ϵ = Emittance, ρ = Electrical Resistivity]

INDEX TO MATERIALS AND PROPERTIES (CONTINUED)

[$\Delta L/L_0$ = Thermal Linear Expansion, λ = Thermal Conductivity
c_p = Specific Heat, ϵ = Emittance, ρ = Electrical Resistivity]

INDEX TO MATERIALS AND PROPERTIES (CONTINUED)

[$\Delta L/L_0$ = Thermal Linear Expansion, λ = Thermal Conductivity
c_p = Specific Heat, ϵ = Emittance, ρ = Electrical Resistivity]

Date:

Evaluation of	"Thermophysical and Electrical Properties of Metal Matrix Composites," P.D. Desai, T.K. Chu, T.C. Chi, R.A. Matula, and H.H. Li, TEPIAC, CINDAS Report 56, 264 pp., 1979.

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